IRON

APPLIED TO

RAILWAY STRUCTURES:

COMPRISING

An Abstract of Results of Experiments

CONDUCTED UNDER THE AUTHORITY OF THE COMMISSIONERS APPOINTED BY HER MAJESTY TO INQUIRE INTO THE APPLICATION OF IRON TO RAILWAY STRUCTURES.

WITH PRACTICAL NOTES;

AND ILLUSTRATED BY PLATES AND DESCRIPTIONS

OF SOME OF THE

Principal Railway Bridges.

BY

G. DRYSDALE DEMPSEY, C.E.

LONDON:
PUBLISHED BY ATCHLEY & CO., 106, GREAT RUSSELL STREET, BEDFORD SQUARE;
AND TO BE HAD OF
SIMPKIN & CO., STATIONERS' HALL COURT.—MANCHESTER: THOMPSON & CO.
LEEDS: SLOCOMB.—EDINBURGH: BELL & BRADFUTE; AND EDMONSTON & DOUGLAS.—GLASGOW: M'PHUN.
DUBLIN: ROBERTSON.—PARIS: GIDE & CO.—MANHEIM: ARTERIA & FONTAIN.
NEW YORK: WILEY; AND APPLETON & CO.—BOSTON: LITTLE & BROWN.
PHILADELPHIA: CARY & HART.
1850.

LONDON:
SAVILL AND EDWARDS, PRINTERS, CHANDOS STREET,
COVENT GARDEN.

IRON APPLIED TO RAILWAY STRUCTURES.

INTRODUCTION.

A HISTORY of the application of iron to the construction of bridges, or a description of the varied forms in which the material has been employed for this purpose, would be both unnecessary in this work and beyond its intended limits. Unnecessary, because the engineering profession are to be supposed acquainted with the main facts of the history, and the leading distinctions of the forms; and, beyond our limits, as requiring an extension of space and a minuteness of detail, compatible only with a much larger and more expensive book. Nevertheless, there are some considerations referring to both the history and the construction which require statement in this place, in order that the present position of the subject may be understood, and the object and value of the latest contribution duly appreciated.

All the earlier bridge structures of iron were designed for the ordinary traffic which passes upon common roads, the great dissimilarity of which, from that which occurs upon railways, is too obvious to need much definition. The effects of these two descriptions of traffic upon the bearing structure differ equally in nature and amount, arising from the greater speed maintained and weight impelled in the one case than in the other. Thus, a load of two tons passing at a maximum rate of speed of ten miles per hour, as of a stage coach, or a load of four tons drawn at a speed of three miles per hour, as of a loaded road-waggon, may evidently be provided for with a bridge which would be utterly incapable of sustaining a load of twenty to thirty tons, impelled at a speed of thirty or forty miles per hour, as of a heavy locomotive engine. For the latter purpose, indeed, any material would appear to require vastly increased dimensions of parts from those sufficing for the former; and when the nature of the present mode of railway propulsion is considered, and due import ascribed to the action of the locomotive machinery in producing concussions upon the sustaining structure, it will be understood that such a metal as cast-iron cannot be *economically* adapted to the purpose without a skilful arrangement of parts, and exact determination of dimensions. For while, on the one hand, the facilities of forming it into large masses of similar outline and dimensions by the process of casting, present a great inducement to its employment; yet, on the other, the crystalline and rigid nature of its formation betraying the want of fibre and liability to instantaneous rupture, are inherent disqualifications for a service in which great weight and high velocity are combined with constant vibration and liability to concussion.

Despite these severe conditions, however, the examples of cast-iron bridges for the older highways, were not to be disregarded or avoided by the engineers of the new, and with the celebrated structures of Colebrook Dale and Southwark before them, the designers of railway-works at once boldly determined to enlist in their own hard service, the material so well applied by Rowland Burdon and John Rennie in a less imposing duty. Burdon's bridge, thrown over the Wear at Sunderland, consists of one arch having six parallel ribs, each of which is built up or composed of separate segmental castings, corresponding with the voussoirs of a stone arch. The span of this arch is 236 feet, and each of the six ribs is composed of 105 blocks or frames of cast-iron, each five feet deep and four feet in width or thickness, the several parts of each block being connected with bars and cotters of wrought iron. The ribs are fixed at the distance of six feet from each other, and are braced together with tubes and bridles of cast iron. The arch contains 214 tons of cast iron and 46 tons of malleable iron. This bridge was projected in 1790, constructed at Rotherham, and completed within a period of three years.

Southwark Bridge, over the Thames, (opened on the 25th March, 1819), consists of three arches, and contains a total weight of 4585 tons of metal. The dimensions of the arches, &c., are as follows:—Centre arch, span 240 feet; rise 24 feet. Span of side arches, each 210 feet. Piers 24 feet thick. Roadway over bridge 28 feet wide, and footways seven feet each. Metal in centre arch 1665 tons. Ditto in side arches 2920 tons. In this bridge the ribs of the arches are plates, fitted together in segments, and braced and connected, transversely, with diagonal frames of cast iron.

In these and many other bridges of cast iron, the *arch* form was adopted, and the separate castings introduced as segments, in a manner similar to that of the voussoirs of stone bridges. In smaller works, such as bridges for crossing canals, &c., each arched rib was formed in one piece, and the several ribs arranged in parallel positions, inserted in the masonry at the springing, and connected with cross ties of malleable iron.

The materials of the common road-ways over iron bridges being in some degree elastic, have the effect of reducing the vibration and concussion produced by passing loads, and thus relieve the rigid metal of the arches of their injurious consequences. In the construction of the permanent way of railways, however, thorough stiffness is an indispensable requirement; and hence arises another cause of the iron bridges over which they are carried being unavoidably required to perform a much more severe duty than ordinary road-way bridges.

The principle of the arch, affording the greatest strength and power of resistance, presents peculiar facilities for railway-bridge construction, and it has accordingly been adopted in a large number of cases. On the earlier railways especially many examples are afforded, and iron arches of varied spans, from 25 to 100 feet, may be found without difficulty. On the London and Birmingham line several are to be found of the smaller dimension, and the great iron arch by which the Manchester and Birmingham Railway is carried over Fairfield-street at Manchester, 128 feet 9 inches in span, may be instanced as a successful structure upon the same principle.

The arch form, however, when applied to large spans, requires a great height from the springing to the crown, and this condition is generally inconvenient, and frequently impossible, in railway bridges, where the difference of level of the roads crossing and crossed is an enforced necessity, the amount of which it is desirable, both for economy of construction and accessibility of traffic, to reduce as much as possible. Thus, in the Fairfield-street bridge just mentioned, of which the span is 128 feet 9 inches, the rise of the intrados of the arch is only 12 feet, and the curve thus presents a remarkable flatness. The difficulty of obtaining even so small a proportion of elevation as this in some cases led to the substitution of other forms of construction for that of the arch; and to this kind of difficulty are due some of the finest examples of engineering expedients of which the art of bridge-building can boast. In bridges chiefly constructed of cast iron, two principal forms have been resorted to for these cases, viz., first, the suspension or "bow-string" bridge, and second, the level or horizontal girder bridge. The railway suspension-bridge as distinguishable from those usually constructed with chains for ordinary traffic, must be considered as an adapted variety of the arch form, the structure combining arches of cast iron with rods of malleable iron, by which the railway is suspended from the arches, the springing points of which are tied together with malleable bars, as the ends of a bow are retained by its string. By this combination, the level of rails is kept a little above the line of the springing of the arches, which rise above and on either side of the railway. A bridge of this kind, erected on the London and Birmingham Railway, carries the line over the Grand Junction Canal at Long Buckby. This bridge is oblique to the direction of the canal, and is 70 feet in span on the skew face. The arches rise about six feet and are filled in with open cast iron work, so as to preserve horizontal lines above and below. The clear width of the railway is 26 feet 9 inches, and the arch on each side of it comprises two ribs, fixed parallel at a distance of about three feet from each other, and connected with cast iron transverse bracing frames of open diagonal pattern. Through the centre of each of these frames a wrought iron suspending rod passes vertically, and, being secured with keys in a boss cast upon the frame above, passes below through one end of a transverse girder of cast iron, and is keyed firmly into it. These bracing frames being fixed at the distance of six feet apart, support the suspension rods and transverse girders at the same distance, and upon these girders the rails are carried upon timber blocks, and the intermediate spaces are filled with open gratings of cast iron. Below each of the arched ribs two horizontal rods of wrought iron are carried in slings, and firmly fixed at the ends, being intended to aid the ribs in resisting extension on their lower flanges. A similar bridge was constructed to carry the same railway over the Regent's Canal, at Camden Town, near London.

In the horizontal level girder bridge the arch form is entirely dispensed with; and the whole required strength is sought in the depth of section given to the girders, auxiliary aid being intended by the addition of wrought iron bars or rods. One of the earliest examples of this form of bridge was erected in 1840 to carry the Northern and Eastern Railway over the Lea river, near Tottenham, and consists of two parallel girders, level from end to end, placed at such distances apart that the railway is carried between them. Each girder consists of two castings, joined together with a vertical joint at the middle of the length, the clear span being 66 feet, bearing on wall at each end 2 feet, total length of girder 70 feet, length of each casting, half of this, or 35 feet. These girders are 3 feet in depth, and each of them is trussed with two sets of malleable iron bars, one set being fixed on each side of the girder, and consisting of two rows of bars 6 inches wide and 1 inch in thickness. At points about 22 feet from either end of the girder, saddles are fixed below the bottom flange, and at each end of the girder, bosses are cast upon it near the top flange. The malleable iron bars are keyed through these bosses, and descending obliquely, are secured to the saddles by means of turned wrought iron pins 3 inches in diameter. Between the saddles, horizontal bars are passed along under the middle portion of the girder, 22 feet in length, and thus complete the trussing. In bridges of this kind, the rails are carried upon transverse timbers or girders, which are supported in pockets cast upon the inner side of each main girder, either actually upon, or a little above, the lower flange of it.

Subsequently, this form of horizontal girder bridge was applied to much larger spans for railway purposes, the girders being similarly compounded of two, or if necessary three, castings with vertical joints, and furnished with sets of malleable iron truss bars. One of these bridges erected near Chester, over the Dee river, comprising three spans, each 96 feet in width, having suffered fracture, became the subject of professional and public consideration, and the seeming liability of such bridges to accidental and unwarned failure, induced a general doubt of their safety. This doubt quickly ripened, under the influence of fear, into an outcry against the use of cast iron in any form for railway bridges, and to this outcry we are indebted for Her Majesty's commission of certain "right trusty," or "trusty" and "well-beloved" of her subjects "to inquire into the conditions to be observed by engineers in the application of iron in structures exposed to violent concussions and vibration."

Of the Report lately presented by these Commissioners, it is the object of the following pages to present a summary account, together with an abstract of the appendices, and digest of the evidence collected under the authority of the Commission.

THE COMMISSION "APPOINTED TO INQUIRE INTO THE APPLICATION OF IRON TO RAILWAY STRUCTURES:"

ITS MEMBERS, OBJECT, AND REPORT.

The Commission is dated August 27th, 1847, and addressed to Lord Wrottesley; R. Willis, Esq., of Cambridge; Captain H. James, R.E.; G. Rennie, Esq., C.E.; W. Cubitt, Esq., C.E.; and E. Hodgkinson, Esq. The purpose of the appointment is stated to be that of "inquiring into the conditions to be observed by engineers in the application of iron in structures exposed to violent concussions and vibration." The Commissioners are directed to "endeavour to ascertain such principles and form such rules as may enable the engineer and mechanic, in their respective spheres, to apply the metal with confidence, and to illustrate by theory and experiment the action which takes place under varying circumstances in iron railway bridges which have been constructed." The Commission authorizes the calling of witnesses and the reporting of proceedings, and appoints Lieut. D. Galton, R.E., as secretary to the commissioners.

In exercise of the powers with which they were thus invested, the Commissioners proceeded to make experiments, examine witnesses, and finally to address a report to Her Majesty of these several proceedings and their results. This report is contained in two bulky "Blue books" of the usual superficial dimensions—viz., 13½ by 8½ inches, whereof one contains the report, appendices, evidence, &c., and the other is filled with illustrative figures or plates. The first of these volumes is entitled, "Report of the Commissioners appointed to inquire into the application of iron to railway structures," and the other is designated "Plans[1] referred to in the Report of the Commissioners," &c. The contents of these two volumes are briefly as follows:—

Vol. I., Paper No.	1.—The Commission . . . . occupying	1 page.
	2.—Report of the Commissioners	10 pages.
	3.—Appendices A and A A. Experiments by E. Hodgkinson, Esq.	180 „
	4.—Appendix B. Experiments by the Rev. R. Willis, Capt. H. James, R.E., and Lieut. D. Galton, R.E. .	83 „
	5.—Analysis of Evidence received by the Commissioners, and List of Witnesses	21 „
	6.—Minutes of Evidence	94 „
	7.—Appendix No. 1. Letter from P. W. Barlow, Esq.	2 „
	8.—Appendix No. 2. Letter from J. Glynn, Esq. . .	4 „
	9.—Appendix No. 3. Letter from J. U. Rastrick, Esq.	4 „
	10.—Appendix No. 4. Letter from R. Stephenson, Esq., &c.	13 „
	11.—Appendix No. 5. Letters from W. H. Barlow, Esq.	1 page.
	12.—Appendix No. 6. Letters and Report from W. Fairbairn, Esq.	8 pages.

[1] We would hope we may, without presumption, refer to the Commissioners' adoption of this common misnomer. The term "Plan" is technically applied only to a geometrical ***horizontal*** delineation of a subject, as distinguished from ***vertical*** elevations and sections. The volume referred to contains all these, and yet the Commissioners allow it to be entitled "Plans," while its contents are called "Plates," "Drawings," &c. It must be admitted, that such little discrepancies and carelessnesses as this may lead to confusion, while they certainly do not consist with the idea of scientific precision.

As a record of the bulk of our common knowledge upon the subjects of cast iron structures, the volume here presented is doubtless an interesting and valuable work, although it must be admitted that the success of the Commissioners in fulfilling their instructions to "*ascertain such principles and form such rules as may enable the engineer and mechanic, in their respective spheres, to apply the metal with confidence*," is not wholly beyond the possibility of doubt. The principal papers of a theoretical and experimental character are the Appendices A, A A, and B, and the extended reputation of Professors Hodgkinson and

Willis is sufficient guarantee of the ability of these contributions. The evidence collected from the nineteen gentlemen who furnished verbal or written evidence to the Commissioners, is, as might have been expected, full of dissimilar opinions and statements, while it contains much matter of practical value and interest. These features, of course, appear in the report itself, which, as a summary of the whole of the results of the Commissioners' labours, claims our first attention.

THE COMMISSIONERS' REPORT.

The leading points of the Report may be made apparent by arranging the substance of its contents under the following heads:—

1. *Present rules for proportioning the load of girders to their breaking-weights.* The dimensions of cast iron girders intended for sustaining stationary loads, such as water-tanks and floors, are usually so proportioned that their breaking-weight shall be *three times* as great as the load they are expected to carry, or in some cases *four or five times* as great. But when the girders are intended for railway bridges, and therefore subject to much concussion and vibration, greater strength is given to them by altering the above proportions, and making the breaking-weight *from six to ten times* as great as the load, according to the practice of different engineers. On the other hand, some consider that *one-third* of the breaking-weight is as safe a load in the latter case as in the former.[2]

2. *Nature of former experiments, and of those now required, and questions to be examined.* The proportions and forms at present employed for iron structures have been generally derived from numerous and careful experiments, made by subjecting bars of wrought or cast iron of different forms to the action of weights, and thence determining by theory and calculation such principles and rules as would enable these results to be extended and applied to such larger structures and loads as are required in practice. But the experiments were made by dead pressure, and only apply, therefore, to the action of weights at rest. On the

---

[2] The variation of the proportion of breaking-weight to load adopted—viz., *from three times to ten times*, is truly a sufficient proof of the absence of well-established principles, and an ample justification of the labours of the Commissioners, even if their inquiries had furnished twenty Blue-books instead of two. Any "common-sense" and non-professional person, required to select between these two limits, would, in all probability, forego all further reasoning and experiment, by "striking the average," and to this identical result, or very near it, the scientific labours of the Commissioners will presently appear to have led them, as they declare, that "to allow the greatest load to be *one-sixth* (!) of the breaking-weight is hardly a sufficient limit for safety, even upon the supposition that the beam is perfectly sound."

contrary, from the nature of the railway system, the structures employed therein are necessarily exposed to concussions, vibrations, torsions, and momentary pressures of enormous magnitude, produced by the rapid and repeated passage of heavy trains. It soon appeared, in the course of the inquiry, that the effects of heavy bodies moving with great velocity upon structures, had never been made the subject of direct scientific investigation; and as it also appeared, that in the opinion of practical and scientific engineers, such an inquiry was highly desirable, the attention of the Commissioners was early directed to the devising of experiments for the purpose of elucidating this matter.

The Commissioners accordingly proposed to examine the questions involved in the inquiry under the two following heads—viz.

1. Whether the substance of metal which has been exposed for a long period to percussions and vibrations undergoes any change in the arrangements of its particles by which it becomes weakened? And,

2. What are the mechanical effects of percussions and of the passage of heavy bodies in deflecting and fracturing the bars and beams upon which they are made to act?

Upon the first of these questions the Commissioners cite observations and conjectures to the following effect:—Many curious facts elicited in evidence show that pieces of wrought iron which have been exposed to vibration, such as the axles of railway carriages, the chains of cranes, &c. employed in raising heavy weights, frequently break after long use, and exhibit a peculiar crystalline fracture and loss of tenacity, which is considered by some engineers to be the result of a gradual change produced in the internal structure of the metal by the vibrations. In confirmation of this, various facts are adduced, as, for instance, that if a piece of good fibrous iron have the thread of a screw cut upon one end of it by the usual process of tapping, which is always accompanied by much vibratory action, and if the bar be then broken across, it will be found that the tapped part is a good deal more crystalline than the other portion of the bar. Others contend that this peculiar structure is the result of an original fault in the process of manufacture, and deny this effect of vibration altogether; whilst some allege that the crystalline structure can be imparted to fibrous iron in various ways, as, by repeatedly heating a bar red-hot, and plunging it into cold water, or by continually hammering it, when cold, for half an hour or more. One witness thinks the various appearances of the fracture depend much upon the mode in which the iron is broken. The same piece of iron may be made to exhibit a fibrous fracture when broken by a slow heavy blow, and a crystalline fracture when broken by a sharp short blow. Temperature alone has also a decided effect upon the fracture; iron broken in a cold state shows a more crystalline fracture than the same iron warmed a little. The same effects are by some supposed to be extended to cast iron.

The Commissioners, having apparently become sufficiently puzzled by these different theories of the cause of the alleged change of structure from fibrous to crystalline, produced in wrought iron, "endeavoured to examine this question experimentally in various ways," which they report as follows:—A bar of cast iron, three inches square, was placed on supports about 14 feet asunder. A heavy ball was suspended by a wire 18 feet long from the roof, so as to touch the centre of the side of the bar. By drawing this ball out of the vertical position at right angles to the length of the bar, in the manner of a pendulum, to any required distance, and suddenly releasing it, it could be made to strike a horizontal blow upon the bar, the magnitude of which (*i. e.* the blow) could be adjusted at pleasure, either by varying the size of the ball or the distance from which it was released. Various bars (some of smaller size than the above) were subjected, by means of this apparatus, to successions of blows, numbering in most cases as many as 4000, the magnitude of the blow in each set of experiments being made greater or smaller as occasion required. The general result obtained was, that when the blow was powerful enough to bend the bars through *one-half* of their *ultimate deflection*, (that is to say, the deflection which corresponds to their fracture by dead pressure,) no bar was able to stand 4000 of such blows in succession; but all the bars (when sound) resisted the effects of 4000 blows, each bending them through *one-third* of their ultimate deflection.

Other cast iron bars, of similar dimensions, were subjected to the action of a revolving cam, driven by a steam-engine. By this they were quickly depressed in the centre, and allowed to restore themselves, the process being continued to the extent even, in some cases, of a hundred thousand successive periodic depressions for each bar, and at the rate of about four per minute. Another contrivance was tried, by which the whole bar was also during the depression thrown into a violent tremor. The results of these experiments were, that when the depression was equal to one-third of the ultimate deflection, the bars were not weakened. This was ascertained by breaking them in the usual manner with stationary loads in the centre. When, however, the depressions produced by the machine were made equal to one-half of the ultimate deflection, the bars were actually broken by less than nine hundred depressions. This result corresponds with and confirms the former.

By other machinery, a weight equal to half of the breaking-weight was slowly and continually dragged backwards and forwards from one end to the other of a bar of similar dimensions to the above. A sound bar was not apparently weakened by ninety-six thousand transits of the weight.

From these observations, the Commissioners proceed to deduce as follows:—

It may on the whole, therefore, be said, that as far as the effects of reiterated flexure are concerned, cast iron beams should be so proportioned as scarcely to suffer a deflection of one-third of their ultimate deflection. And as it will presently appear that the deflection produced by a given load, if laid on the beam at rest, is liable to be considerably increased by the effect of percussion, as well as by motion imparted to the load, it follows that *to allow the greatest load to be one-sixth of the breaking-weight is hardly a sufficient limit for safety, even upon the supposition that the beam is perfectly sound.*

The practical truth of the approximate rule thus derived will evidently depend, not only on the correctness of the experiments, which is not to be questioned, but also on the correspondence of the several conditions under which they were made, with those affecting the structures referred to; and since the application of the rule would impose a large increase of section in girders designed to support railway bridges, every item of the data upon which it is founded claims the scrutiny of the inquirer. An occasion for describing the experiments and their immediate results, will hereafter occur in our notice of the Appendix in which they are narrated.

The Report proceeds to state, that in wrought iron bars no very perceptible effect was produced by 10,000 successive deflections by means of a revolving cam, each deflection being due to half the weight which, when applied statically, produced a large permanent flexure.

The mechanical effects of percussions and moving weights upon beams.—To ascertain these effects a great number of experiments have been made by the Commissioners, and from these it appears that bars of cast iron, of the same length and weight, struck horizontally by the same ball, (by means of the apparatus before described for long-continued impact,) *offer the same resistance to impact, whatever be the form of their transverse section, provided the sectional area be the same.* Thus, a bar, $6 \times 1\frac{1}{2}$ inches in section, placed on supports about 14 feet asunder, *required the same magnitude of blow to break it in the* *middle, whether it was struck on the broad side or the narrow one*, and similar blows were required to break a bar of the same length, the section of which was a square of three inches, and, therefore, of the same sectional area and weight as the first.[8]

From another course of experiments made with the same apparatus, it appeared, among other results, that the deflections of wrought iron bars were nearly as the velocity of impact.

By another set of experiments, it was found that beams of cast iron, loaded to a certain degree with weights spread over their whole length, and so attached to them as not to prevent the flexure of the bar, resisted greater impacts from the same body falling on them, than when the beams were unloaded, in the ratio of two to one.

Another series of experiments was made to compare the mechanical effect produced by weights passing with more or less velocity over bridges, with their effect when placed at rest upon them. The general result thus obtained was, that the deflection produced by a load passing along a bar was greater than that produced by placing the same load at rest upon the middle of the bar, and that this deflection was increased when the velocity was increased. Thus, for example, when the experimental carriage, loaded to 1120 pounds, was placed at rest upon a pair of cast iron bars, 9 feet long, 4 inches broad, and an inch and a half deep, it produced a deflection of six-tenths of an inch; but when the carriage was caused to pass over the bars at the rate of ten miles an hour, the deflection was increased to eight-tenths, and continued to increase as the velocity was increased, so that, at thirty miles per hour, the deflection became an inch and a half; that is, more than double the statical deflection.

Since the velocity so greatly increases the effect of a given load in deflecting the bars, it follows that a much less load will break the bar when it passes over it, than when it is placed at rest upon it, and accordingly, in the example above selected, a weight of 4,150 pounds is required to break the bars if applied at rest upon their centres; but a weight of 1778 pounds is sufficient to produce fracture if passed over them at the rate of 30 miles an hour.

It also appeared that when motion was given to the load, the points of greatest deflection, and, still more, of the greatest strains, did not remain in the centre of the bars, but were removed nearer to the remote extremity of the bar.

---

[8] These startling results, which seem to belie all previously held principles upon the subject, cannot fail to arrest the attention of the inquirer.

The bars, when broken by a travelling load, were always fractured at points beyond their centres, and often broken into four or five pieces, thus indicating the great and unusual strains they had been subjected to.

The Commissioners endeavoured to discover the laws which connect these results with each other and with practice, and for this purpose a small and delicate apparatus was constructed to examine the phenomena in their simplest form—viz., in the case of a single weight traversing a light elastic bar; for the weight, in its passage along the bar, deflects it, and thus the path, or *trajectory* of the centre of the weight, instead of being a horizontal straight line, as it would be if the bar were perfectly rigid, becomes a curve, the form of which depends upon the relation between the length, elasticity, and inertia of the bar, the magnitude of the weight, and the velocity imparted to it. If the form of this curve could be perfectly determined in all cases, the effects of travelling loads upon bars would be known; but unfortunately the problem in question is so intricate, that its complete mathematical solution appears to be beyond the present powers of analysis, except in the simplest and most elementary case—viz., that in which the load is so arranged as to press upon the bar with one point of contact only, or, in other words, the load is considered as a heavy moving point. In practice, on the contrary, a single four-wheeled carriage touches each rail or girder in two points, and a six-wheeled engine with its tender has five or six points in contact on each side. This greatly complicates the problem.

The small apparatus here referred to, is so arranged as to comply with the simple condition, that the load shall press upon one point only of the bar, and is also furnished with a contrivance by which the effects of various proportions of the mass of the bar to that of the load can be examined. From the nature of the problem, it is convenient to consider, in the first place, the forms of the trajectories that are described, and the corresponding deflections of the bar, when the mass of the bar is exceedingly small compared with that of the load. Having obtained these, under different relations of the length of the bridge, its statical deflection, and the velocity of the passing load, the Commissioners desired to investigate, in addition, the effect which a greater proportional mass of the bar or bridge has upon the deflections. In this research they obtained the eminent assistance of G. Stokes, Esq., M.A., and now Lucasian Professor in the University of Cambridge, whose analytical investigation is quoted and duly acknowledged by the Rev. R. Willis, in his Preliminary Essay to the experiments recorded in Appendix B. In order to produce appreciable deflections in the experiments, the ratio of the load to the inertia of the bearing bar was necessarily far greater than any that actually occurs in the loading of railway bridges, and in these enforced conditions of the experiments, and the subsequent reduction of the results, we have two possible sources of errors that may seriously invalidate the character of the theory. This difficulty is candidly stated by the Commissioners, in whose experiments the weight of the load was from three to ten times that of the bar; whereas, in actual bridges of about 40 feet span, the weight of the engine and tender is very nearly the same as the weight of that half of the bridge over which it passes, and in large bridges the weight of the load is much less than that of the bridge. The Commissioners consider that their experiments have established the fact that an increase of velocity given to any given load causes an increase in the deflection of the supporting girder, and further, that the ratio of this increase of deflection to the statical deflection [4] of the girder, diminishes, while the length of the girder is increased. In our subsequent notice of these experiments the precise results will be briefly presented; but in the meantime the following conclusion of the Rev. R. Willis's "Preliminary Essay," which precedes Appendix B., may be quoted as showing the difficulty of comparing the experimental with the ordinary results, and the amount of practical importance belonging to them. "The experiments carried out at Portsmouth by Captain James and Lieutenant Galton had given the important and valuable result, that velocity imparted to a load increased the deflections of the bar or bridge over which it passed above those which it would have produced if set at rest upon the same bridge. The amount of this increase was also of so alarming a magnitude, that it seemed incredible that it should have escaped observation in practical cases. Accordingly, when the Commissioners visited the bridges at Ewell and Godstone, the effects there observed, although of the same character, were infinitely less in amount."

"It became, therefore, necessary to investigate the laws of these phenomena; and as analysis, even in the hands of so accomplished a mathematician as Mr. Stokes, failed to give tangible results, excepting in cases limited by hypotheses that separated the problem from practical conditions, it became necessary to carry on also experiments directed to the express object of elucidating the theory,

---

[4] By "statical deflection," is meant "that which would be produced by the load set at rest on the centre of the bridge."

and tracing its connexion with practice. I have already stated that the time which remained to me for this purpose, as well as the limited funds placed in the hands of the Commission, were together insufficient to admit of either constructing the apparatus, or performing the experiments, with the minute and delicate accuracy required for the precise numerical results usually sought for in physical investigations. But my object was rather to elucidate general laws, guided by theory, than to obtain independent numerical results, and I trust that this purpose has been sufficiently answered."

"It has been shown that the phenomena in question exhibit themselves in a highly developed state when the apparatus is on a small scale, but that, *on the contrary, with the large dimensions of real bridges, their effects are so greatly diminished as to be comparatively of little importance, except in the cases of short and weak bridges traversed with excessive velocities.* The theoretical and experimental investigation, which is the subject of the above essay, will, however imperfect, serve to show that such a diminution of effect, in passing from the small scale to the large, is completely accounted for."

The only actual trials of bridges which the Commissioners made to determine the effect of velocity in augmenting deflection, were upon two bridges erected upon the Croydon and Epsom, and South Eastern railways, and known as the "Ewell Bridge," and the "Godstone Bridge," each of which supports the railway over a road. "A scaffold was constructed, which rested on the road, and was therefore unaffected by the motion of the bridge, and a pencil was fixed to the under-side of one of the girders of the bridge, so that when the latter was deflected by the weight of the engine or train, either placed at rest or passing over it, the pencil traced the extent of the deflection upon a drawing-board attached to the scaffold. An engine and tender, which had been in each case liberally placed under our orders by the directors of the Companies, were made to traverse the bridges at different velocities, or rest upon them, at pleasure. The span of the Ewell Bridge is 48 feet, and the statical deflection due to the above load rather more than one-fifth of an inch. This was slightly but decidedly increased when the engine was made to pass over the bridge, and at a velocity of about 50 miles per hour an increase of one-seventh was observed. As it is known that the strain upon a girder is nearly proportional to the deflection, it must be inferred, that in this case the velocity of the load enabled it to exercise the same pressure as if it had been increased by one-seventh, and placed at rest upon the centre of the bridge. The weight of the engine and tender was 39 tons, and the velocity enabled it to exercise a pressure upon the girder equal to a weight of about 45 tons. Similar results were obtained from the Godstone bridge." [5]

Longitudinal compression and extension of cast and wrought iron. In addition to the above experiments, the Commissioners made many " for the purpose of supplying data for completing the mechanical theory of elastic beams. If a beam be in any manner bent, its concave side will be compressed, and its convex side extended, and an exact knowledge of the laws which govern its compression and extension must precede any accurate general theory of its deflections, vibrations, and ruptures." The law usually assumed—viz., that the longitudinal compressions and extensions are, within certain limits, proportional to the forces by which they are produced, " although very nearly true in some bodies, is not, perhaps, accurately true for any material. Experiments have therefore been made to determine with precision the direct longitudinal extension and compression of long bars of cast and wrought iron. The extensions were determined by attaching a bar 50 feet in length and 1 inch square, to the roof of a lofty building, and suspending weights to its lower extremity. The compressions were ascertained by enclosing a bar 10 feet long and 1 inch square in a groove, placed in a cast iron frame, which allowed the bar to slide freely without friction, and yet permitted no lateral flexure. The bar was then compressed by means of a lever loaded with various weights. Every possible precaution was taken to ensure accuracy. The following formulæ were deduced for expressing the relation between the extension and compression of a bar of cast iron, 10 feet long and 1 inch square, and the weights producing them respectively—

$$\text{Extension,}\quad w = 116{,}117\,e - 201{,}905\,e^2$$
$$\text{Compression,}\quad w = 107{,}763\,d - 36{,}318\,d^2$$

Where w is the weight in pounds acting upon the bar, e the extension, and d the compression in inches. And the formulæ deduced from these, for a bar one inch square, and of any length, are—

$$\text{For extension,}\quad w = 13{,}934{,}040\,\frac{e}{l} - 2{,}907{,}432{,}000\,\frac{e^2}{l^2}$$

$$\text{For compression,}\quad w = 12{,}931{,}560\,\frac{d}{l} - 522{,}979{,}200\,\frac{d^2}{l^2}$$

[5] "The Godstone bridge was the first upon which the experiments in question were tried, and the scaffold and registering apparatus was by no means so complete and steady as that which was used for the Ewell bridge. The actual quantity to be measured (about a quarter of an inch) was so small that the least unsteadiness in the apparatus would affect its correct registration."—(*Preliminary Essay*, by the Rev. R. Willis.)

where l is the length of the bar in inches. These formulæ were obtained from the mean results of four kinds of cast iron. The mere tensile strength of cast iron, derived from these experiments, is 15,711 pounds per square inch, and the ultimate extension $\frac{1}{600}$ of its length, and this weight would compress a bar of iron of the same section $\frac{1}{775}$ of its length. It must be observed that the usual law is very nearly true for wrought iron.

"Many denominations of cast iron have got into common use, of which the properties had not yet been ascertained with due precision. Seventeen kinds of them have been selected, and their tensile and crushing forces determined. Experiments have also been made upon the transverse strength and resistance of bars of wrought and cast iron, acted upon by horizontal as well as vertical forces. These experiments will be found to exhibit very fully the deflections and sets of cast iron, and the defect of its elasticity. The bars which were experimented upon by transverse pressure were of sections varying from one inch square to three inches square, and of various other sections, and the actual breaking-weights show that the strength of a bar one inch square should not be taken as the unit for calculating the strength of a larger casting of similar metal, although the practice of doing so has been a prevalent one; for it appears that the crystals in the portion of the bar which cools first are small and close, whilst the central portion of bars two inches square, and three inches square, is composed of comparatively large crystals, and bars of three inches square in section, planed down on all sides alike to three quarters of an inch square, are found to be very weak to resist both transverse and crushing pressure. Hence it appears desirable, in seeking for a unit for the strength of iron of which a large casting is to be made, that the bar used should equal in thickness the thickest part of the proposed casting."

In the remaining portion of the Report, the Commissioners refer to the information they have collected respecting the qualities of various kinds of cast iron, and the respective properties of the hot blast and cold blast iron. They mention, with approval, a recommendation "that engineers, in contracting for a number of girders, should stipulate that they should not break with less than a certain weight, (leaving the mixture to the founder,) and cause one more than the required number to be cast. The engineer may then select one to be broken, and if it break with less weight than that agreed upon, the whole may be rejected." A general description of the several kinds of iron bridges for railways follows, and the Commissioners report, in conclusion, that, "considering the attention of engineers has been sufficiently awakened to the necessity of providing a superabundant strength in railway structures, and also considering the great importance of leaving the genius of scientific men unfettered for the development of a subject as yet so novel and so rapidly progressive as the construction of railways, we are of opinion that any legislative enactments with respect to the forms and proportions of the iron structures employed therein would be highly inexpedient.

"We would, however, direct attention to the general conclusions we have arrived at from our own experiments, and from the information supplied to us, namely:—

"That it appears advisable for engineers, in contracting for castings, to stipulate for iron to bear a certain weight instead of endeavouring to procure a specified mixture.[6]

"That to calculate the strength of a particular iron for large castings, the bars used as a unit should be equal in thickness to the thickest part of the proposed casting.

"That, as it has been shown that, to resist the effects of reiterated flexure, iron should scarcely be allowed to suffer a deflection equal to one-third of its ultimate deflection, and since the deflection produced by a given load is increased by the effects of percussion, it is advisable that the greatest load in railway bridges should in no case exceed one-sixth of the weight which would break the beam when laid on at rest *in the centre.*[7]

"That, as it has appeared that the effect of velocity communicated to a load is to increase the deflection that it would produce if set at rest upon the bridge; also that the dynamical increase in bridges of less than 40 feet in length is of sufficient importance to demand attention, and may even[8] for lengths of 20 feet,

---

[6] The "proof weight" being already commonly adopted as a condition by engineers in contracting for cast iron girders, this recommendation by the Commissioners is to be understood as an approval on their part of an existing practice, not the suggestion of a new one.

[7] If this proposition is to be understood in the precise terms in which the Commissioners have expressed it, and since the effect of a load *on the centre* of a beam is double that of a load *distributed over its length*, it follows that the ultimate strength of a railway bridge should be equal to *twelve times* (!) that of the "greatest load" that can be put upon it. For the consolation of those who have to combine economy with sufficiency in their designs, it is to be remarked, however, that the rule here suggested appears about as empirical as many of those already observed in the practice of engineers. We are not favoured with the Commissioners' reason or reasons for doubling the allowance for "reiterated flexure," in order to provide for "the effects of percussion," and are therefore without the means of examining the grounds of this extraordinary conclusion.

[8] The misplacement of this little word, "even," is likely to lead to a false inference. The ratio of the increased deflection to the statical deflection, *diminishes* as the length of the bridge is

become more than one-half of the statical deflection at high velocities, but can be diminished by increasing the stiffness of the bridge; it is advisable that, for short bridges especially, the increased deflection should be calculated from the greatest load and highest velocity to which the bridge may be liable; and that a weight which would statically produce the same deflection should, in estimating the strength of the structure, be considered as the greatest load to which the bridge is subject. For the method of calculating this increased deflection, we beg to refer to Appendix B.

"Lastly: the power of a beam to resist impact varies with the mass of the beam, the striking body being the same; and by increasing the inertia of the beam without adding to its strength, the power to resist impact is, within certain limits, also increased. Hence it follows that weight is an important consideration in structures exposed to concussions.

"Whilst, however, we lament that the limited means which have been placed at our disposal, and the great time required for such investigations, have compelled us to leave in an imperfect state, or even to neglect altogether, many interesting and important branches of experimental inquiry, we trust that the facts and opinions which we have been enabled to collect will serve to illustrate the action which takes place under varying circumstances in iron railway bridges, and enable the engineer and mechanic to apply the metal with more confidence than heretofore."

Appendix A contains a record of experiments made by E. Hodgkinson, Esq., "directed principally (though not wholly) to determine the effects of impacts and vibrations upon iron." The deviation from truth of the law [9] usually assumed, that "the longitudinal compression and extension of iron within certain limits are directly proportioned to the external forces by which they are respectively produced," having been experimentally shown by the author, and reported in the sixth volume of the "Transactions of the British Association for the Advancement of Science," he obtained permission to make some "expe-

---

increased. The above words should, therefore, have been arranged thus: "And may, for lengths of 20 feet, become *even* more," &c. For taking this liberty with the Commissioners' text, we have their own authority in the following sentence of their Report:—"Supposing, for example, the mass of the travelling load and of the bridge to be nearly equal, the increase of the statical deflection at the highest velocities for bridges of 20 feet in length and of the ordinary degree of stiffness, may be more than one-half; whereas, for bridges of 50 feet in length, the increase will not be greater than one-seventh, and will rapidly diminish as greater lengths are taken." (p. 13.)

[9] Known by the name of 'Dr. Hooke,' who first proposed it.

riments on the extension and compression of rods of iron, in order to deduce from them, if possible, the general relations between the weights and the changes of length produced. To numerous experiments respecting impacts, occupying 27 Tables in this Appendix, and to others made to determine the direct tensile and crushing strength of iron, not previously tried—besides some of smaller magnitude—the following experiments are added:—1st, To determine with precision the direct longitudinal extensions and compressions of long bars of cast and wrought iron, by weights varied by equal increments, up to that producing, or nearly producing fracture; 2nd, To seek for general formulæ, connecting the weights with the corresponding longitudinal tensions and compressions of cast iron, and likewise, if practicable, with the "sets," or permanent alterations of the length of the rods remaining after the removal of the external forces, in order that the former may be directly applied to the determination of the situation of the neutral line, and the strength of cast iron beams of every form of section; 3rd, To determine, with equal precision, the deflection of horizontal bars produced by various transverse pressures, and to compare the effects with those produced by impacts; and, 4th, To seek for general formulæ connecting the transverse pressure, the deflection, and the set remaining after the pressure was removed."

Tensile strength of cast iron, from various parts of the United Kingdom.—Seventeen kinds of iron used, embracing Low Moor, Clyde, Blaenavon, Calder, Coltness, Brymbo, Bowling, and Anthracite from Ystalyfera and Ynis-cedwyn. Specific gravity ranging from 6·906 to 7·181. Form of transverse section of specimens, cruciform. Breaking-weight per square inch of section from 5·602 tons to 7·949 tons, except the Clyde iron No. 3, of which the breaking-weight per square inch of section reached 10·477 tons. Mr. Morries Stirling's iron, composed of Calder No. 1, hot blast, mixed and melted with about 20 per cent. of malleable iron scrap, had a breaking-weight of 11·502 tons per square inch of section. Another quality, composed of No. 1, hot blast, Staffordshire iron, mixed and melted with about 15 per cent. of common malleable iron scrap, had a breaking-weight of 10·474 tons.

Tensile strength of cast iron of different forms of section.—Forms of section used—*cruciform*, extreme breadth four inches and depth three inches; uniform thickness of arms 64 inches; *rectangular*, 2·3 inches × 1·75 inches; and *circular*, 2·26 inches diameter; the intended area in all the forms being equal to four square inches. Mean breaking-weight per square inch of the *cruciform* section varied from 6·253 tons to 6·784 tons; of the *rectangular*, from 6·115 tons to

6·267 tons; and of the *circular* from 6·614 tons to 6·993 tons. From these results it may be inferred that little or no difference in the tensile strength of cast iron arises essentially from the form of its section.

Strength of cast iron in various sectional forms to resist crushing.—The iron used was Low Moor, No. 1. The first set of experiments were upon *cylinders*, the specimens being in two proportions,—viz., having diameter of section equal to height, and having a height equal to double the diameter of section. In the first cases, the mean crushing-weight per square inch of section varied from 27·512 tons to 28·810 tons. In the second cases, it varied from 24·988 tons to 29·769 tons. The second set of experiments were upon *triangular prisms*, of which the bases were intended to be equilateral triangles, with sides one inch in length: with a height of specimen of one inch, the mean crushing-weight per square inch of section was 29·905 tons, and with a height equal to two inches it was 31·045 tons. The third set of experiments were upon *rectangular prisms*. The base of each prism was intended to be one square inch, with a height of one inch, the mean crushing-weight per square inch of section was 28·112 tons, and with a height of two inches, 26·437 tons.

Comparative power to resist crushing of cast iron from different parts of the kingdom.—The irons employed were those known as Low Moor, Nos. 1 and 2; Clyde, Nos. 1, 2, and 3; Blaenavon, Nos. 1 and 2; Calder, No. 1; Coltness, No. 3; Brymbo, Nos. 1 and 3; Bowling, No. 2; three anthracites, and Mr. M. Stirling's second and third qualities. The specimens were cylinders three quarters of an inch in diameter, and three quarters of an inch and one inch and a half in height. The general mean crushing-weight per square inch of section varied from 27·004 tons (Low Moor Iron, No. 1) to 49·109 tons, (Blaenavon, No. 2). Mr. Stirling's irons required crushing-weights of 54·640 tons and 64·403 tons respectively, the third quality showing the greater resistance.

Ratio of tensile to crushing resistance in cast iron.—The torn specimens being of a cruciform section, and those crushed of a circular section and cylindrical form. The resistances being reduced to those due to a square inch of section, the ratio is seen to vary from 1:4·518 to 1:6·735. The average ratio of the whole (omitting Mr. Stirling's as being a compound iron) is 1:5·6603.

Power of beams of cast iron to sustain long-continued impact.—"The effect of impact and vibration upon structures was a leading object of inquiry with the Commission; and the first series of experiments instituted upon this subject was, to determine the power of beams to sustain impacts many times repeated.

For this purpose sixteen bars were cast, all from Blaenavon iron No. 2, and five at least of the sixteen were found to be slightly defective at some place where they gave way. Whether these small defects were more numerous than would be found in practice, it would be difficult to determine. Six of the bars were 15 feet long and 3 inches square, and placed on supports 13 feet 6 inches asunder; seven were each 10 feet long and 2 inches square, and 9 feet between the supports; and three were each 5 feet long, 1 inch square, and 4½ feet between the supports. Of these bars, six were bent through one-third of their ultimate deflection at each blow, and five of them bore each 4,000 blows without breaking; the sixth was broken at a flaw with 1,085 blows. One large bar, bent by impact through five-twelfths of its ultimate deflection, was broken at a defective place with 1,350 blows. Of six bars bent by blows through half their ultimate deflection, five were broken with less than 4,000 blows each; one with 29; another with 127, &c. The only bar which bore the 4,000 blows was one of the smallest kind, or 1 inch square. Of three bars, one bent to seven-twelfths, and two to two-thirds the ultimate deflection, all were broken; the two latter with 127 and 474 blows respectively; the former required 3,700 blows to break it. Of ten bars of Low Moor Iron No. 2, each 10 feet long and 2 inches square, placed on supports 9 feet asunder, and struck in the middle with long-continued impacts, as before, four broke at defective places, and two at sound ones. Three were subjected to impacts bending them through one-third of their ultimate deflection, and bore the test without fracture: of three bent by blows through half their ultimate deflection, two were broken; those bent through two-thirds were all broken. On the whole, it appears that no bar but one, and that a small one, stood 4,000 blows, each bending it through half its ultimate deflection; but all the bars, when sound, stood that number of blows, each bending them through one-third their ultimate deflection. It must, however, be borne in mind, that a cast iron bar will be bent to one-third of its ultimate deflection with less than one-third of its breaking-weight, laid on gradually; and one-sixth of the breaking-weight laid on at once, would produce the same effect, if the weight of the bar was very small compared with the weight laid on it. Hence the prudence of always making beams capable of bearing more than six times the greatest weight which will be laid upon them." Mr. Hodgkinson makes the following

Remarks on some of the leading results of horizontal impacts upon cast iron beams:—"1st. The bars in Tables I., II., and III. were of the same sectional area, length, and weight nearly, but differed in the form of their transverse section. They were placed on supports at the same distance (13½ feet) asunder, and struck horizontally by the same ball, 603 lbs. weight, suspended by a radius of 17 feet 6 inches. From the results, it appears that *the beam 3 inches square, and the rectangular beams* 6 × 1½ *inches section, struck on the broader and narrower sides respectively, had all very nearly the same strength to resist impact.* These conclusions are drawn from a mean between two experiments in each case. In Table XV., six bars, each 2 × 1 inch section, and 5 feet long, were laid on supports 4½ feet asunder, and all struck by the same ball, 75½ lbs. weight, with arcs of a radius 17 feet 6 inches. Three of them were struck on the broader and three on the narrower sides, and their mean chords of impact to produce fracture were 70 inches and 71·67 inches respectively, or nearly the same, agreeing with the results of the experiments upon the former bars.

"2nd. In Table IV. the bars were of the same dimensions in section as those in Table I., or 3 inches square, but the distance between the supports was reduced one-half. The resulting breaking deflection, 1·23 inch, was somewhat greater than one-fourth of that in Table I., or 4·875 inches, and the vertical descent to produce fracture was nearly one-half, but rather more, the depth fallen through in the two cases being ·639 inch and 1·238 inch. Comparing, in like manner, the half and whole bars in Tables V. and II., the depths are ·5521 inch and 1·2071 inch respectively. This result, coupled with the former one, shows that the depth fallen through to break the half bar is nearly half of that required to break the whole one. Comparing the results in Tables VIII. and XII., and also Tables X. and XIII., it appears also that a bar of half the length of another resists with nearly half the energy, but somewhat more.

"3rd. The experiments in Tables I., II., III., IV., and V. afford illustrations of some of the conclusions in the large generalization of Dr. Young, deduced from neglecting the inertia of the beam. (*Nat. Phil., Lecture XIII.*) 'The resilience of a prismatic beam, resisting a transverse impulse, follows a law very different from that which determines its strength, for it is simply proportional to the bulk or weight of the beam, whether it be shorter or longer, narrower or wider, shallower or deeper, solid or hollow. Thus, a beam 10 feet long will support but half as great a pressure without breaking, as a beam of the same breadth and depth which is only 5 feet in length; but it will bear the impulse of a double weight striking against it with a given velocity, and will require that a given body should fall from a double height in order to break it.'

"4th. The experiments in Table VI. were made to compare the effects of striking a bar midway between the centre and one support with those of striking similar bars at the centre, as in Table IV. The great impacts, so near to the support in these cases, would necessarily cause it to yield slightly, and thus increase the resisting powers of the bars to sustain impact. In experiments made by the author several years ago, given in the Fifth Report of the British Association, page 112, on bars 1 inch square—some subjected to impacts in the middle, and others at half the distance between the middle and one support—the chord of impact necessary to produce fracture was nearly equal in the two cases. The ratio of the deflections, from equal impacts at the middle and at one-fourth span, was nearly constant under different increasing degrees of impact; the deflections at the middle from equal impacts being to those at one-fourth span as 10 : 7 nearly. The relative ultimate deflections of the beam in the middle, and at a point half way between the middle and one end, ought to be as 10 : 7·5 nearly.

"5th. The bars in Tables VIII., IX., and X. were all of the same iron and size, and the only difference was in the weights of the striking balls. The distances fallen through, and the work done by the balls to produce fracture being respectively ·3159 and 190·488 with the 603 lbs. ball, 1·2856 and 194·447 with the 151¼ lbs. ball, and 3·0506 and 230·32 with the 75½ lbs. ball, affording a good illustration of the resistance from the weight of the bar.

"6th. The bars in Table XI. were of the same iron (Blaenavon No. 2) as the others, but remelted, to ascertain the effect of melting this iron a second time, without mixture, upon its power to bear impact. The strength to resist blows was increased, but the iron was harder and much more unsound than before. The work done by the ball to break the beam in each case was increased in the ratio of 261 to 194.

"7th. The deflections in cast iron beams were always found to be greater than in proportion to the velocity of impact; whilst in wrought iron they were nearly constant with impacts of very different velocities. This fact shows that there is a falling off in the elasticity of cast iron through impact, analogous to that through pressure. The difficulty of obtaining a satisfactory theory of the power of cast iron beams to sustain impact is considerably increased by this falling off in elasticity, but it is hoped that the varied nature of these experiments will tend much to reduce it. The note in page 4, and the approximate formulæ to which it relates,[10] connecting pressure with impact, and based on

---

[10] The formulæ here referred to are as follows:—"In an experimental inquiry, by the Author, into the power of beams to sustain impact from a body striking them horizontally, or falling directly upon them, it was shown that, if blows of the same magnitude were given upon the middle of a

the supposition of perfect elasticity, apply, therefore, only to small impacts upon *cast* iron beams."

Appendix AA contains an *experimental inquiry to determine the strength of wrought iron tubes*, by E. Hodgkinson, Esq., F.R.S., &c. The formulæ investigated by the author of this paper for the strength of tubes of three forms of section tried in the preliminary experiments, may be quoted as follows:—

Cylindrical Tubes.—"The strength of a cylindrical tube, supported at the ends, and loaded in the middle, is expressed by the formula:

$$w = \frac{\pi f}{a l}(a^4 - a'^4);$$

Where l is the distance between the supports, a, a', the external and internal radii; w, the breaking-weight; f, the strain upon a unit of section, as a square inch, at the top and bottom of the tube, in consequence of the weight w; $\pi = 3{\cdot}14159$. From this formula we obtain—

$$f = \frac{w l a}{\pi (a^4 - a'^4)}$$

---

beam, either by elastic or inelastic bodies of the same weight, the same effect would be produced. The striking body appears to proceed with the beam after impact, as if they were one mass. (Fifth Report of the British Association, 1835.) In the inquiry above, formulæ were deduced according to these conclusions, both for horizontal and vertical impacts, taking into consideration the effect of the weight or inertia of the body struck. Formulæ for horizontal impacts are comparatively simple, and that given below is the same as that of Tredgold. (Essay on the Strength of Iron, Art. 302.)

$$\frac{h w^2}{w + w'} = \frac{p e}{2}$$

When w = the weight of the striking body, h = the height due to the velocity of impact, p = a pressure which, applied gradually to the middle of the beam, would bend it to an extent equal to that produced by the impact, e = the deflection caused by that pressure, and w' = a weight equivalent to the resistance of the beam, from its inertia. If the resistance of the body struck had been uniform, the right side of the equation would have been twice as great, or $p e$; but in a beam, the resistance to flexure is nothing in the commencement, and it increases in proportion to the flexure. The preceding formula gives the impact, in terms of the height fallen through by the ball or striking body; but in the experiments, the deflections are given in terms of the chord of the arc of impact, and the following formula would represent them:—

$$d = wc\sqrt{\frac{e'}{p' r (w + w')}}$$

Where d = the deflection of the beam, c = the chord of the arc, r = the radius, from the points of suspension to the centre of the ball, p' = any pressure applied to bend the beam, e' = the deflection caused by that pressure, and the rest as before. The value of w' depends upon the weight of the beam, and as a mean, it may be taken at one-half of the weight of the beam between the supports, as was shown by the experiments in the Report above mentioned."

As the value of f depends upon the quality of the material, and ought to be nearly constant in tubes of the same nature, as in wrought iron, it may be useful to give the value of f from each of the experiments in Mr. Fairbairn's Report. In doing this, it will be necessary to explain that the value of w includes, besides the weight laid on at the time of fracture, the pressure from the weight of the tube between the supports, this last being equal to half that weight. Computing the results, and taking the dimensions in inches, we obtain—

		Mean.
Experiment 1.	$f = 33{,}456$ lbs.	lbs. tons.
„ 2.	$f = 33{,}426$	29,887 = 13·34.
„ 3.	$f = 35{,}462$	
„ 4.	$f = 32{,}415$	
„ 5.	$f = 30{,}078$	
„ 6.	$f = 33{,}869$	
„ 7.	$f = 22{,}528$	
„ 8.	$f = 22{,}655$	
„ 9.	$f = 25{,}095$	

Fracture took place, in all cases, either by the tube failing at the top, or tearing across at the rivet holes. This happened on the average, as appears from the mean result, when the metal was strained to $13\frac{1}{3}$ tons per square inch, or little more than half its full tensile strength." Experiments made by the author several years ago, showed that "the strength of the plates, however riveted together with one row of rivets, was reduced to about one-half the tensile strength of the plates themselves; and if the rivets were somewhat increased in number, and disposed alternately in two rows, the strength was increased from one-half to two-thirds or three-fourths at the utmost."

Elliptical Tubes.—" The strength of these is expressed by the formula—

$$w = \frac{\pi f (b a^3 - b' a'^3)}{l a}$$

Where a, a' are the semitransverse external and internal diameters, b, b', the semiconjugate external and internal diameters, the transverse axis being vertical, and the rest as before, w including in all cases the pressure from the weight of the tube. We have, therefore,

$$f = \frac{w l a}{\pi b a^3 - b' a'^3)}$$

and from the experiments on tubes, of which the section was an ellipse, we have—

		Mean.
In experiment 20.	$f = 36{,}938$ lbs.	lbs. tons.
„ 21.	$f = 29{,}144$	37,089 — 16·55
„ 24.	$f = 45{,}185$	

Rectangular Tubes.—" The transverse strength of tubes, of which the section is a rectangle, and the thickness of the plates at the top and bottom equal, the sides being of any thickness at pleasure, is expressed by the following formula:—

$$\frac{2f(bd^3 - b'd'^3)}{3ld}$$

Where d, d', are the external and internal depths respectively, b, b', the external and internal breadths, and the rest as before.

$$\text{Whence } f = \frac{3wld}{(2bd^3 - b'd'^3)}$$

The value of f obtained from experiment No. 14, of Mr. Fairbairn, is 18,495 lbs. = 8·2566 tons, but this is much below what was deduced from experiments made by the author, and of the results of which the following is an abstract:—

Length of Tube.		Weight of Tube.		Distance between Supports.		Depth of Tube.	Breadth of Tube.	Thickness of Plates of Tube.	Last Observed Deflection.	Corresponding Weight.	Breaking Weight.	Value of f for crushing strain.
Ft.	In.	Cwt.	Qrs.	Ft.	In.	Inches.	Inches.	Inch.	Inches.	Tons.	Tons.	Tons.
31	6	44	3	30	0	24 nearly	16 nearly	·525	3·03	56·3	57·5	19·17
31	6	24	1	30	0	24 „	16 „	·272	1·53	20·3	22·75	14·47
31	6	10	1	30	0	24 „	16 „	·124	1·20	5·04	5·53	7·74
		lbs.	oz.							lbs.	lbs.	
8	2	78	13	7	6	6 „	4 „	·132	·66	9416	9976	23·17
8	2	38	11	7	6	6 „	4 „	·065	·32	2696	3156	15·31
8	2	...	...	7	6	6 „	4 „					
4	$2\frac{1}{8}$	10	12	3	9	3 „	2 „	·061	·435	2464	2464	24·56
4	$3\frac{1}{4}$	4	15	3	9	3 „	2 „	·03	·13	560	672	13·42

" These tubes were made without joints in the middle, to remove the anomalies caused by riveting: the value of f will be increased by that circumstance in the tubes with thicker plates. Looking at the breaking-weights of the tubes varying only in thickness, we find a great falling off in the strength of the thinner ones; and the values of f show that in these—the thickness of the plates being ·525, ·272, and ·124 inch—the resistance per square inch will be 19·17, 14·47, and 7·74 tons respectively. The breaking-weights here employed do not include the pressure from the weight of the tube. The value of f is usually constant in questions on the strength of bodies of the same nature, and represents the tensile strength of the material; but it appears from these experiments, that it is variable in tubes, and represents their power to resist crippling."

Beyond the important object of ascertaining how far the value of f is affected by changing the thickness of the metal, the other dimensions of the tube being the same, (as shown in the foregoing abstract,) Mr. Hodgkinson desired to determine the strength of tubes similar in all their proportions, but differing in actual dimensions, so as to apply the results obtained upon the experimental tubes, to such as might be constructed for actual railway service. The results of experiments instituted to elucidate this point showed that the power of the lineal dimensions on which the strength of *similar* tubes, varying in size, depends, varied from 1·846 to 2·271, the *mean* power being 1·942. "In several of these experiments the tubes gave way, by the metal at the top becoming wrinkled; and as it appears that in most of the cases the strength was somewhat lower than as the square of the lineal dimensions, we may perhaps with safety adopt 1·9 instead of 2, to represent that power."

Another object was to "ascertain the strength of a uniform tube, bent transversely, to bear a load in any part of its length," and also "whether tubes tapering in thickness from the middle towards the ends, according to theory, would be equally strong in every part? By theory, the strength of the same tube varies inversely, as the rectangle of the segments into which the distance between the supports is divided by the load in any part; and we obtain, from the table (of experiments) the rectangles of the segments, and corresponding breaking-weights, of the tubes which were broken by forces applied in more than one part." Hence, in uniform tubes of the external dimensions of those experimented upon, and of different thickness of plate, (from one-eighth to half an inch,) we have a mean from the inverse ratio of the rectangles of the segments $= \frac{142}{100}$, and a mean from the ratio of the actual breaking-weights $= \frac{146}{100}$. "Whence it appears that the mean theoretic to the experimental ratio, from all the experiments, is as 142 to 146; and hence that the tubes may apparently be reduced in strength and thickness towards the ends, in the ratio indicated by theory."

Besides the detailed records of the experiments here referred to, the appendix contains those of others intended to serve as data for determining the dimensions &c. of tubular bridges—such as the Conway and Britannia—and also elaborate computations for this purpose. We have no space for any intelligible abridgment of these calculations, which, however interesting in pursuing the inquiries proposed by the author, involve too much mathematical reasoning to invite the attention of practical men generally. And although (since the extent to which these and other experimental results were *adopted* in designing the Britannia and Conway tubes has become the subject of keen controversy) it is a delicate —almost invidious task to predicate aught upon the subject; it is, we believe, an admitted fact, that the tubes were constructed *before* the completion of the inquiry, and that intelligent experience supplied the omissions, or compensated for the delays of mathematical investigation.

Appendix B contains a report of experiments for determining the effects produced by causing weights to travel over bars with different velocities, made in Portsmouth Dockyard, and at Cambridge, by the Rev. R. Willis, F.R.S., Jacksonian Professor, &c., Capt. H. James, R.E., F.R.S., and Lieut. D. Galton, R.E., together with experiments made in Portsmouth Dockyard on the strength of rectangular bars of cast iron; on the effects of reiterated depressions of iron bars, by revolving cams, of traversing weights, &c. &c., with a "Preliminary Essay," by the Rev. R. Willis, on the effects produced by causing weights to travel over elastic bars. The bars in all the experiments were laid in parallel pairs, and tested by passing a loaded car at various rates of velocity over them. The first series of these experiments were made with bars of cast iron 9 feet long between the points of support, 1 inch broad and 2 inches deep. The weight of the load was increased at each transit till one or both of the bars broke, the velocities being obtained by letting the car run down an inclined plane from various heights. In *Experiment No.* 1, a weight of 1120 lbs., at rest on the centre of the bars, produced a central deflection of 1·26 inches and a set of ·28 inch. A weight of 2242 lbs. increased the deflection to 4·1 inches and the set to 1·34 inch, and a weight of 2256 lbs. broke one of the bars. In *Experiment No.* 2 the greatest observed central deflection was 4·06 inches and set 1·43 inch, the load being 2126 lbs. The breaking-load was 2154 lbs., and the fracture of the bar showed a flaw in the material. In *Experiment No.* 3, the deflection produced by the load of 1120 lbs. at rest on the centre of the bars equalled ·90 inch, and the set ·27 inch. The maximum observed central deflection was 3·98 inches, set 1·5 inch, load 2280 lbs. A weight of 2294 lbs. broke both of the bars. In *Experiment No.* 4, the car at rest on the centre of the bars, weight 1120 lbs., caused a deflection of ·88 inch, and a set of ·20 inch. The same load impelled at the velocity of 15 feet per second, or 10·2 miles per hour, produced a central deflection of 1·24 inch and a set of ·21 inch. 1760 lbs. at the same velocity produced a central deflection of 3·00 inches and a set of ·91 inch. An ultimate load of 1876 lbs. broke one of the bars. *Experiment No.* 5, load 1120 lbs. at rest, deflection at centre ·86 inch, set ·25 inch. Same load at velocity of 10·2 miles per hour increased deflection to 1·11 inch, the set remaining the same. A load of 1844 lbs. increased the deflection to 4·17 inches, the set to 1·59 inch, and eventually broke one of the bars. In *Experiment No.* 6, a load of 1120 lbs. at rest on centre of bars produced a deflection of ·62 inch and a set of ·12 inch. The same load, passed at the rate of 10·2 miles per hour; increased the deflection to ·74 inch, with the same set as before; a load of 1792 lbs. deflected the bars 2·90 inches, with a set of ·67 inch, and a load of 1816 lbs. broke one of the bars. In *Experiment No.* 7, a load of 1120 lbs. at rest upon the centre of the bars caused a deflection of ·64 inch, and a set of ·12 inch. The same load propelled at the velocity of 24 feet per second, or about 16½ miles per hour, increased the central deflection to 1·02 inch, and the set to ·15 inch. A load of 1412 lbs. at the same speed produced a deflection of 3·16 inch and a set of ·72 inch, and a load of 1440 lbs. broke both bars. In *Experiment No.* 8, 1120 lbs. at rest on centre as before showed a deflection of ·65 inch, and a set of ·11 inch. A velocity of 24 feet per second increased the deflection to ·87 inch and the set to ·14 inch. 1496 lbs. at the same velocity produced a deflection of 3·94 inches, and a set of 1·07 inch, and 1524 lbs. broke both bars. In *Experiment No.* 9, a load of 1120 lbs. at rest on the centre deflected the bar ·74 inch, with a set of ·18 inch. The same load at a velocity of 24 feet per second caused a deflection of 1·14 inch, and 1580 lbs. at same velocity produced a deflection of 3·08 inches and a set equal to ·68 inch. 1604 lbs. broke both bars. In *Experiments* 10, 11, and 12, 1120 lbs. at rest showed deflections from ·95 to 1.17 inch, and a velocity of 29 feet per second, or nearly 20 miles per hour, increased them from 1·80 to 2·54 inches. The breaking-weights varied from 1204 to 1240 lbs. at the same velocity, and the greatest observed deflections from 1·80 to 3·36 inches. In *Experiments* 13, 14, and 15, the velocity was increased to 33 feet per second, or about 22½ miles per hour, the statical deflections being from ·81 to 1·30 inch, the breaking-loads from 1148 to 1288 lbs., and the last observed deflections from 2·67 to 3·65 inches. In *Experiments* 16, 17, and 18, the velocity was increased to 36 feet per second, and the greatest breaking-weight was 1204 lbs., the maximum observed deflection being 2·31 inches.

The Second Series comprised 15 experiments upon bars 9 feet long between the supports 1 inch broad and 3 inches deep. The breaking-weights, at rest on the centre, varied from 4126 to 4388 lbs., the maximum central deflection being 2·71 inches. With a velocity of 15 feet per second, the greatest breaking-weight was 3496 lbs, and deflection 2·70 inches. A velocity of 29 feet per second reduced the breaking-weight to 3167 lbs. 36 feet per second reduced it to

2468 lbs., greatest deflection 2·08 inches. A velocity of 43 feet per second reduced the greatest breaking-weight to 2242 lbs., deflection 1·87 inch. From these results, it appears that a small load moving at a great velocity breaks a bar before it has suffered the whole of the deflection which a greater load produces, moving at a less velocity.

In the third series, comprising ten experiments, the bars employed were 9 feet long between supports, 4 inches broad, and 1½ inch deep, being calculated to break with the same statical pressure as the bars used in the *second series*, but being more flexible. The statical breaking-weights were 3968 pounds, and 4332 pounds; the greatest observed deflection (produced by 3968 pounds), 4·55 inches, and 3·96 inches. By giving to the load a velocity of 15 feet per second, the breaking-weights became 3296 pounds, and 3303 pounds; maximum observed deflection 4·85 inches. With a velocity equal to 29 feet per second, the breaking-weight was reduced to 2670 pounds, and the maximum deflection was 4·14 inches; at 36 feet per second, a load of 2176 pounds broke one of the bars in one experiment, and 2060 pounds broke both the bars in another experiment—greatest observed deflection 3·88 inches. At 43 feet per second, 1778 pounds broke both bars, the greatest deflection being 1·54 inch.

In the fourth series, comprising four experiments, the bars used were of Clyde iron (No. 3), 9 feet long, 2 inches broad, and 3 inches deep. The statical deflection produced by 1120 pounds was ·16 and ·17 inch; statical breaking-weights 9088 pounds, with ultimate deflection of 1·91 inch, and 9882 pounds, with ultimate deflection of 2·33 inches. With a velocity of 43 feet per second, a load of 3614 pounds produced a deflection of 1·54 inch, (the statical deflection of 3643 pounds being only ·61 inch), and a load of 2996 pounds produced a deflection of 1·14 inch, while its statical deflection (as proved by bringing it again to a state of rest) was only ·52 inch.

The following sixteen experiments were made upon bars of different scantlings—viz., 13 feet 6 inches long, 1 inch broad, and 3 inches deep; on bars of Mr. M. Stirling's iron, on bars of wrought iron and of Clyde iron, on steel bars, and on cast-iron bars of various degrees of curvature; but the results do not appear entitled, by exactness or immediate practical importance, to any detailed notice in this abstract.

Three series of experiments were conducted on bars 9 feet long between the supports, showing the amount of deflection obtained when the weight is brought on suddenly without impact, and also the breaking-weights. The results are as follow:—*First series.* Bars of 9 feet long, 1 inch broad, and 2 inches deep. Mean weight of bars, 66·5 pounds.

Velocity in feet, per second	0	15	24	29	33	36
Mean breaking-weight in pounds per pair of bars,	2281	1842	1523	1216	1213	1176

Second Series. Bars 9 feet long, 1 inch broad, and 3 inches deep. Mean weight of bars 93·5 pounds.

Velocity in feet per second . .	0	15	29	36	43
Mean breaking-weight in pounds	4235	3400	3044	2406	2182

Third Series. Bars, 9 feet long, 4 inches broad, and 1½ inch deep. Mean weight of bars 195 pounds.

Velocity in feet per second . .	0	15	29	36	43
Mean breaking-weight in pounds	4150	3299	2670	2118	1708

Experiments on railway bridges to ascertain the increase of deflection produced by the velocity of the load.

Ewell Bridge, (*Epsom and Croydon Railway.*) Span 48 feet. Two girders to support each line of rails. Depth of girders at centre, 3 feet 6 inches. Width of bottom flange, 20 inches; thickness of ditto, 3 inches. Weight of two girders, 20 tons. Weight of platform between these girders, 10 tons. Total weight of half the bridge, 30 tons. Weight of engine, 25·2 tons; weight of tender, 13·8 tons. Total 39 tons.

Velocity in feet per second	0	25	30·9	32·3	53·7	75
Deflection in decimal parts of an inch	·215	·215	·230	·225	·245	·235

The Commissioners remark, that " the deflections do not increase steadily; but this could hardly be expected, from the many causes of disturbance."

Godstone Bridge, (*South Eastern Railway.*)—Span 30 feet. Three girders support the roadway. Depth of girders at centre, 3 feet. Width of bottom flange, 15 inches; thickness of ditto, 2¼ inches. Weight of two girders, 15 tons. Weight of platform between these girders, 10 tons. Total weight of half the bridge, 25 tons. Weight of engine, 21 tons; weight of tender, 12 tons. Total, 33 tons.

Velocity in feet per second	0	22	40	73
Deflection in decimal parts of an inch	·19	·23	·22	·25

The remainder of *Appendix B* consists of records of some miscellaneous experiments comprising a series, made by statical pressure, on the strength of rectangular bars of cast iron, and others with the cam, &c., by Capt. H. James, R.E., F.R.S. The records of these experiments are tabulated, and the actual mean reduced breaking-weights shown in juxtaposition with the calculated breaking-weights as obtained from Barlow's formula—

$$s = \frac{l w}{4 a d^2} = 7620,$$

and from the formula given in Hodgkinson's edition of "Tredgold:"

$$w = \frac{4{\cdot}5 \times b d^2 s}{l}$$

the value of s having been obtained by these writers from the breaking-weights of each kind of iron, in bars 1 inch square, and 4 feet 6 inches long. This comparison distinguishes the kind of iron experimented upon, and confirms the value of mixing and remelting in order to obtain the strongest quality of metal.

The experiments made with the cam, &c., were devised to ascertain the effect produced upon iron bars by reiterated strains, corresponding to loads equal to some fractional part of the breaking-weight. The cams were worked by steam machinery, and the bars depressed and restored to their original position for a great number of times. Two cams were employed, one of which imparted a highly vibratory motion to the bar during the deflection, the other gently depressed the bar, and suddenly released it when the full deflection had been obtained. From four to seven depressions were made per minute. Three bars tested by the former apparatus to a deflection equal to one-third of the statical breaking-weight obtained from similar bars, suffered 10,000 depressions, and afterwards required as much weight to break them as similar bars subjected to dead weights only. Of two bars subjected to a deflection equal to that due to half the breaking-weight, one was broken by 28,602 depressions, and the other sustained 30,000, and did not appear thereby weakened in its resistance to statical pressure. Of the bars tried with the second cam, three sustained 10,000 depressions, each giving it a deflection equal to that produced by one-third of the statical breaking-weight, without suffering any apparent loss of power to resist statical pressure; one broke with 51,538 depressions; and one bore 100,000 without any apparent loss of strength. Three other bars, deflected by the same cam to one-half the extent liable to be produced by the statical breaking-weight, broke with 490, 617, and 900 depressions respectively. "It must therefore be concluded, that iron bars will scarcely bear the reiterated application of one-third their breaking-weight without injury." [11] A bar of wrought iron 2 inches square in section, and 9 feet long between the supports, was subjected to 100,000

[11] We must confess we cannot trace the sequence of this conclusion.

depressions by means of the first mentioned or rough cam, each depression producing a strain corresponding to about five-ninths of the strain that permanently injured a similar bar. These depressions only produced a permanent set of ·015 inch. Three wrought iron bars were subjected to 10,000 depressions each, from the step cam, depressing them through ·333 in., ·666 in., and ·833 in. respectively, without producing any perceptible permanent set. A bar, depressed through 1 in., obtained a set of ·06 in.; and one depressed 300 times through 2 in., acquired a set of 1·08 in. The largest deflection which did not produce any permanent set, appears, by an experiment on a similar bar, to be that due to rather more than half the statical weight which permanently injured it. A small box-girder, of boiler-plate riveted, 6 in. × 6 in. in section, and 9 feet long, was also subjected to depressions by means of the rough cam, principally with the view of ascertaining whether any effect would be produced on the rivets by the repeated strain; but a strain corresponding to 3,752 lbs., repeated 43,370 times, did not produce any appreciable effect."

Of the evidence given by the several witnesses, it is impossible, within our limits, to present any useful abstract. The opinions stated as to the qualities of iron, and rules for determining the dimensions of girders—the topics of principal import to the present inquiry—embrace wide differences, and although mixtures of iron are generally recommended as likely to produce the most serviceable quality, but little definite information can be gleaned from the evidence here offered.

The several appendices, of which a list is given in pages 6 and 7, contain several interesting experiments by Mr. R. Stephenson, Mr. Rastrick, Mr. Fairbairn, Mr. Barlow, and others, some of which are to be esteemed as useful accessions to the records of the properties of iron. These, however, like the bulk of the labours of the Commission, conducted, as they evidently have been, with great industry and talent, require yet much careful examination and arrangement before they can become practically available. Of the special proceedings of the Commissioners, indeed, it is evident from their Report, that the earlier measures were prosecuted with the most care, and that after conducting elaborate experiments, they appear to have agreed in stating opinions rather than drawing conclusions.

DESCRIPTION OF PLATES.

On PLATE I., Figs. 1 and 2 refer to a cast iron compound girder bridge trussed with wrought iron bars, erected to support the Wakefield and Goole Railway over the Knottingley and Goole Canal. The span of the bridge, measured on the face, is 88 feet 6 inches. Each girder comprises three main castings, and three upper castings filling up the spaces above the others, so that the maximum depth at the joints is obtained throughout the girder, and its upper line is horizontal.

Fig. 1 is an elevation of the bridge to the scale of 16 feet to one inch; and Fig. 2 is a vertical transverse section through one of the girders and the filling-piece, drawn to an enlarged scale. The entire depth of the section is 8 feet. The width across the top of the filling-piece is 12 inches, and thickness of flange 2 inches; thickness of web of filling-piece 1¼ inch. The meeting flanges are 8 inches wide; bottom flange of filling-piece 1¾ inch thick; top flange of girder 2 inches thick, and web 2 inches thick. Bottom flange of girders 2 feet by 2¾ inches. Two malleable iron truss bars on each side of each girder, 1 inch thick each, and transverse tie-bars 2 inches wide.

In testing this bridge, the load used consisted of locomotive engines and tenders, equal in weight to one ton per lineal foot of the girders. This load at rest caused a deflection equal to ·02 of a foot in the outside and middle girders, and at a speed of about 25 miles per hour, a deflection of ·02 of a foot in the outside girder, and ·03 of a foot in the middle girder. "The deflection in each case was carefully measured with a spirit level, and the result obtained indicates that where the road is in good order, the deflection is not much increased by speed, but that where the road is out of order, then there is an increase of deflection."

Figs. 3, 4, 5, and 6 represent the girders employed for the iron bridges on the Trent Valley Railway as strengthened with filling-pieces. The clear span is 59 feet 2 inches. Fig. 3 shows an elevation of the girders; fig. 4, a transverse vertical central section; and figs. 5 and 6, enlarged views of the end portion and joints of the girders. The dimensions of the original girder at section fig. 4 are as follow:—Total depth 2 feet 6 inches; top flange, 8 × 2 inches; web, 2 inches thick; bottom flange, 2 feet by 2½ inches. The dimensions of filling-piece at same section are—top flange, 1 foot 3 inches by 1½ inch; web, 2 inches thick throughout; intermediate flange, 1 foot 1½ inch by 1½ inch; bottom flange clipping over top flange of original girder, 12 inches by 1½ inch; depth, 3 feet. Total depth of central section, fig. 4, 5 feet 6 inches. Two sets of wrought iron tension bars on each side of each girder, the bars being 6 inches by 1 inch. The experiments made upon these girders by the engineer, T. L. Gooch, Esq., are thus recorded:—" The weights applied in the experiments consisted of pigs of iron placed as near the centre as practicable, nowhere exceeding 8 feet from it. The weight of the original girder was 18 tons, and of the additional pieces, 7 tons 17 cwt. The first experiment made was previous to the additional pieces being put on, the tension bars being in full action, and the result of various trials upon several girders of like dimensions may be stated as follows:—Weight in tons, 30; deflection in inches, 1¼ to 1½ inch. The second experiment, which was made with more detail, had the additional pieces attached, the tension bars remaining in full action as before. The following were the results:—

Weight in tons . .	10	20	30	40	50	60	70	80	90	100
Deflection in inches,	None perceptible.	0·15	0·24	0·34	0.49	0·64	0·78	0·96	1·10	1·20

This weight was kept on for about a fortnight without any perceptible change, when the load was removed, and the deflections were such that the beam returned completely to its original state. Comparing this result with the first, it will be at once apparent that a very great accession of stiffness and strength was obtained by the use of the additional pieces, and they were accordingly applied to the compound girders on the Trent Valley Railway. It should be observed, however, that although the girders without the additional pieces, in the first experiment, were tested, for the sake of the experiment, at a clear span of 59 feet 2 inches, they were intended for a span of 54 feet 6 inches, and when thus tested in their proper place, by being loaded with a train of the heaviest locomotive engines in motion, the deflection was not found to be more than one-half to five-eighths of an inch."

Figs. 7 to 14 show an elevation, plan, and enlarged details of the Calder Bridge, erected on the line of the Wakefield and Goole Railway. This bridge consists of three spans of 50 feet each on the square. Each of these spans is crossed by compound girders, each in two pieces, bolted together with vertical joints, and trussed with malleable iron bars. Fig. 7 shows an elevation of one set of girders; fig. 8 a plan of the three sets; fig. 9 an end view of girder at the joints; fig. 10, a vertical section near the end of the girder, and through the key which fixes the ends of the tension bars. This figure also shows the transverse bars which connect the parallel sets of girders. Figs. 11 and 12 represent the ends and joints of the girders enlarged; and figs. 13 and 14 are vertical transverse sections of one of the girders, taken at the points of least and greatest depth. Of the three parallel sets of girders which constitute the bridge, the middle set differs from the outer or side girders in being 12 inches deeper than the latter. The greatest depth of the middle girders is 6 feet 2 inches, and least 4 feet 8 inches. The corresponding dimensions of the side girders are 5 feet 2 inches and 3 feet 8 inches. The other dimensions are the same in all the girders—viz., width of top flange 8 inches; width of bottom flange 2 feet, and thickness 2½ inches; thickness of web 2 inches. The tension bars are each 6 inches by 1 inch; and the transverse tie-bars 1½ inch square. This bridge, when tested similarly with that over the Knottingley and Goole Canal, (figs. 1 and 2,) showed a deflection in each of the girders equal to ·01 of a foot, and which remained the same when a velocity of 25 miles per hour was given to the load.

PLATE II. represents the hollow girders of malleable iron for a bridge on the line of the Ardwick Branch Railway, and over the river Medlock. The span of this bridge is 100 feet, and the total length of each girder 108 feet. Five of these girders are arranged parallel to each other, and at such distances apart that the two lines of railway have each a width of 12 feet 6 inches between the girders, and the two roadways are each 12 feet 8 inches in clear width. Each of the girders is 8 feet 9 inches deep at the middle, and 8 feet deep at the ends, being cambered on the top. The girders are formed of iron plates of various thicknesses, from one quarter to one-half an inch, and have two longitudinal cells or compartments in the top; the sides and top are of single plates, but the bottom is of a double thickness of plates. The longitudinal plates in the bottom of the girders and in the top cells are increased in thickness from the ends towards the middle of the girder, while the vertical plates forming the sides are diminished in thickness in the same direction. The three inner girders are 1 foot 8 inches wide, and their top compartments 2 feet 3 inches by 13 inches. The two outer girders are 1 foot 3 inches wide, and their top compartments 1 foot 10 inches by 13 inches. The roadways and railways are planked upon transverse hollow beams, formed of iron plates and angle-iron ribs in the corners riveted through the vertical and horizontal plates. These beams are 12 inches deep, 5 inches wide in the tube, and 10 inches wide over the top and bottom plates, and they are riveted to the sides, and supported upon the projecting bottom plates of the main girders. The joints of the vertical side plates of the main girders are covered externally with strips of plate iron, and have internal ribs, to which the plates and the outside strips are riveted. The longitudinal joints are secured with angle-iron ribs, riveted through the plates. Fig. 1 is a side elevation of the girders, and Fig. 2 a transverse section through the five girders, showing the two lines of railway and the two roadways. Figs. 3 to 7 are enlarged details of the construction of the bridge; fig. 3, a transverse section of one of the outer girders, and fig. 4 a similar section of one of the inner girders. Fig. 5 is a cross section of one of the transverse beams, and figs. 6 and 7 show elevation and bottom plan of end of a girder, with the external plates and strips with which the joints are covered.

PLATE III. exhibits a bridge formed of cast iron plates of a corrugated form, which supports a road at Mount Pleasant, Tonbridge Wells, over the Tonbridge and Tonbridge Wells Branch Railway. This bridge consists of two openings, each 28 feet wide on the face, and the width of the roadway comprises twelve rows of plates, bolted together, through vertical flanges, at the joints. Fig. 1 is an elevation of the bridge; and fig. 2 a plan showing half covered with the cast iron corrugated plates. Fig. 3 is a vertical section of the bridge to an enlarged scale, and figs. 4, 5, 6, and 7 show details of the corrugated plates, and the columns and corbels upon which they are supported at the ends. Mr. P. W. Barlow, the engineer of the work, considers that this method of construction possesses the following advantages: "That there is less depth required between the surface of the road and the soffit of the girder. That one plate assists another, and the weight of a passing load is distributed over the whole bridge, or nearly so; that all lateral vibration is avoided; and that greater safety is obtained by the plates of the bridge being bolted together, as the fracture of any one of them would not be attended by the fall of a load passing over the bridge." An experiment was made upon one of the plates of the bridge represented in Plate III., the bearing being 28 feet, and with the following results:

Load on the centre of the bridge, in tons	3	6	9	11
Deflection in inches	·5	1·0	1·625	2·25

"The bridge, being composed of twelve plates in width, would bear 132 tons in the centre; and, as at least half comes into operation by a load passing over, 66 tons in the middle, or 132 tons all over, may be considered the resisting strength, which is six times what is required. The fact of the assistance rendered by the adjoining plates is shown by the experiments on deflection made on this bridge since it has been executed. The deflection with the heaviest load that has passed over (consisting of a stone truck, which was estimated at 8 tons) amounted to a little under one-eighth of an inch; and this deflection has not been exceeded by any load that has passed over the bridge, as appears from the gauge."

PLATE IV. shows a bridge designed to carry the New Cross Turnpike Road over the North Kent Railway at Lewisham. The construction of this bridge resembles that exhibited in Plate III., in being covered with cast iron plates bolted together, but in this design the plates are not corrugated, and the required stiffness is obtained by casting vertical ribs upon the upper side of them. Fig. 1 represents an elevation of half of the bridge, and fig. 2 a transverse section of half of it. Fig. 3 is a plan of a portion of the plates showing the screwed bolts for connecting them. Fig. 4 is an enlarged section through two of the roadway plates; and fig. 5 is a side elevation of part of one of them, showing the bolt-holes. One of these plates, tested by Mr. P. W. Barlow, 31 feet 6 inches in length, and 3 feet 5½ inches wide, was supported at the ends, so as to leave a length of 28 feet clear of the bearings, and was then loaded with 3¼ tons of bricks distributed over the surface of the plate without bearing on the ribs. The remainder of the load was made up with pig iron, and the following are among the recorded results:

Load in tons	10	16	22	26
Central deflection in inches . . .	1·5	2·5	3·375	4·437

It was found, however, that the bearings had sunk about five-eighths of an inch: deducting this, the deflection of the girder caused by 26 tons appears to be 3·812 inches.

PLATE V. represents a bridge to carry the Ashford, Rye, and Hastings Branch Railway, in the parish of Orlestone, designed by Mr. P. W. Barlow, the engineer of the railway. The span of this bridge is 50 feet, and each girder is composed of three castings, joined with vertical joints and screwed bolts and nuts. The meeting ends of the castings have dovetailed bosses projecting below them, which are embraced by strong clips beneath the lower flange of the girder. Timber beams are fixed transversely between the girders, and rest upon their lower flanges, and upon these beams double diagonal planking is laid in reversed directions, and supports the rails. Fig. 1 is an elevation, and fig. 2 a partial plan of the bridge. Fig. 3 is a transverse section; fig. 4 an end elevation of a girder at one of the joints; and fig. 5 a transverse vertical section through an outside girder, span drilling, and railing. The dimensions of all the girders are as follows: total depth of section, 4 feet; top flange, 8 inches by $1\frac{1}{2}$ inch; web, 2 inches thick; bottom flange, 2 feet by 2 inches.

PLATE VI. shows the girders, &c. for cast iron bridges on the Ambergate, Nottingham, Boston, and Eastern Junction Railway. Figs. 1 to 5 inclusive, refer to girders for a bridge under the railway, 35 feet in span on the square, and 41 feet on the face. Fig. 1 is a transverse section through the six girders, four of which support the railway, and the two outer ones carry a railing or balustrading. Fig. 2 is a side elevation, and fig. 3 a plan of one of these outer girders; and figs. 4 and 5 show a side elevation and plan of one of the inner and stronger girders. The girders are 45 feet 6 inches in length; those on the outside are 2 feet 9 inches deep throughout, and the inner girders are 3 feet 6 inches deep at the middle, and curved down to 1 foot 9 inches at the ends. The rails are laid upon longitudinal beams of timber 16 × 8 inches, which are supported upon transverse joints 12 × 7 inches, fixed at distances of three feet apart, and the ends of which are slightly notched down upon wooden bearings laid upon the lower flanges of the girders.

Fig. 6 is a transverse section of a bridge under the railway, the clear distance between the abutments of which is 25 feet, and the entire length of each girder 27 feet 10 inches. The rails are in this construction carried upon transverse sleepers resting across the cast iron girders, which are 1 foot 11 inches in depth. Arches of brickwork in cement are turned between the girders, springing from their lower flanges, and the six girders are tied together by means of cross bars of malleable iron. The dimensions of the four rail-bearing girders are thus: top flange, $9 \times 2\frac{1}{2}$ inches; web of girder, $2\frac{1}{2}$ inches; bottom flange, $12 \times 2\frac{1}{2}$ inches; bearings on abutments, 12×18 inches each.

Figs. 7 and 8 show the construction of iron girder bridges ten feet between the abutment walls. Fig. 7 is an elevation of one of the girders, and fig. 8 a transverse section through the four girders upon which the rails are supported. These girders, which have timbers fitted and bolted on their sides, are 14 inches in total depth; bottom flange 12 inches by $1\frac{1}{2}$ inch; web, $1\frac{1}{2}$ inch thick at the bottom, and tapered upward. The side timbers are $13\frac{1}{2}$ inches deep, and the total width over each pair, with a girder fixed between them, is 14 inches.

PLATE VII. represents a cast iron compound girder bridge for the Leopold Railway, over the river Arno. The entire bridge comprehends seven spans of 96 feet each. Fig. 1 shows the elevation of half of one of these spans. Fig. 2 is a partial plan; fig. 3, a partial cross section; and figs. 4, 5, and 6 show the ends and couplings of the wrought iron tension bars which are extended horizontally below the girder, and bolted at the ends, between flanges cast on the girders, as shown in fig. 6. The depth of each compound girder at the middle is 7 feet; top flange, 18 inches by $1\frac{5}{8}$ inch; web, $1\frac{3}{4}$ inch thick; bottom flange, 18 inches by $1\frac{5}{8}$ inch. The tension bars are each 6 inches by $1\frac{1}{4}$ inch, and by their couplings at every joint of the castings, ready means are presented of adjusting the length, and consequently the effectiveness of the bars. These means of adjustment, however, are not designed for periodical application, which is not supposed necessary, but simply to be used in putting, at the outset, an "initial strain" upon the bars which shall act always within the limits of their elasticity, and ensure their participation in the load to any desired extent.

PLATE VIII. shows a general elevation of one of the largest cast iron arched bridges yet constructed for railway purposes, and known as the "High Level" bridge over the river Tyne, at Newcastle. This structure combines two distinct thoroughfares, one *over*, and the other literally *through* it, the railway being supported above the crown of the arches, while an ordinary roadway is formed at the level of their springing. The bridge consists of six arches, each 125 feet span, and rising 17 feet 6 inches at the centre. The level of the rails on the upper platform is 108 feet 6 inches above the level of high water. Each arch comprises four ribs of cast iron, arranged parallel to each other, and each being made up of five segments bolted together. The ribs are 3 feet 9 inches deep at the springing, and 3 feet 6 inches at the crown, with flanges 12 inches wide. The metal of the two internal ribs is 3 inches in thickness, that of the external ribs 2 inches. The total sectional area of iron at the crown of the ribs is 644 square inches. The ribs are united at the springing by 24 malleable iron bars, each 7 inches by 1 inch. The railway is supported above the arches upon cast iron pillars, each 14 inches square, and placed 10 feet apart. The roadway is suspended from the arches by means of malleable iron rods, which pass down through the square pillars just described. The level of the railway is about 4 feet above the crown of the arched ribs, and is supported in the middle upon cast iron trough-girders, resting on the pillars, and united by longitudinal timbers, laid with strong planking. The roadway has a height of about 20 feet in the clear. Fig. 2 is a cross section, showing the railway above, the carriage and footways below, the cast iron bracing-frames, pillars, trough-girders, &c.; and fig. 3 is a partial elevation on the inside of one of the ribs, showing the pillars and trough-girders.

PLATE IX. represents a bridge constructed to support Chalk Farm Lane, over the London and Birmingham Railway at Camden Town, and combining malleable iron hollow girders, with cast iron longitudinal ribs on the top, intended to resist the compressive effects of the load. The transverse beams for supporting the roadway are also of cast iron. The span of this bridge is 60 feet. Fig. 1 is an elevation of the girder; fig. 2 a plan; and fig. 3 a partial cross section, showing the mode of construction adopted. Fig. 4 is a plan of the end of a transverse beam, and the cast iron blocking fixed opposite to it within the girder. Figs. 5 and 6 are sections of the transverse beams at the middle and ends of them.

PLATE X. represents a cast iron arched bridge, erected to support the Manchester and Birmingham Railway over Fairfield Street, in Manchester. This arch is 128 feet 9 inches in span, and has a rise of only 12 feet. Each of the ribs consists of nine segmental castings, bolted together, and the spandrilling is filled in with open diagonal panels of cast iron. Fig. 1 is an elevation of the girders; fig. 2 a shortened plan of the top of one of them, showing the total dimensions, and the projecting vertical ribs at the ends, which are built into the masonry of the abutments. Fig. 3 is a vertical transverse section of the rib and spandrilling on the line *AA*, fig. 1. Fig. 4 shows a partial cross section through the upper part of the girders, and the ribbed cast iron covering plates which form the base of the permanent way above. Figs. 5 and 6 represent details of the method adopted of passing the diagonal tie rods in an oblique direction through the girder, and of securing the cast iron struts which have a contrary oblique direction to the sides of it. Figs. 7, 8, and 9 are transverse sections of these ties and struts. The wrought iron ties are held in cast iron sockets, keyed on either side of the girder, and the struts are formed with dovetailed ends, and keyed into suitable sockets cast on the girder.

THE END.

BRIDGE OVER THE KNOTTINGLEY AND GOOLE CANAL.

JOHN HAWKSHAW ESQ^R
ENGINEER.

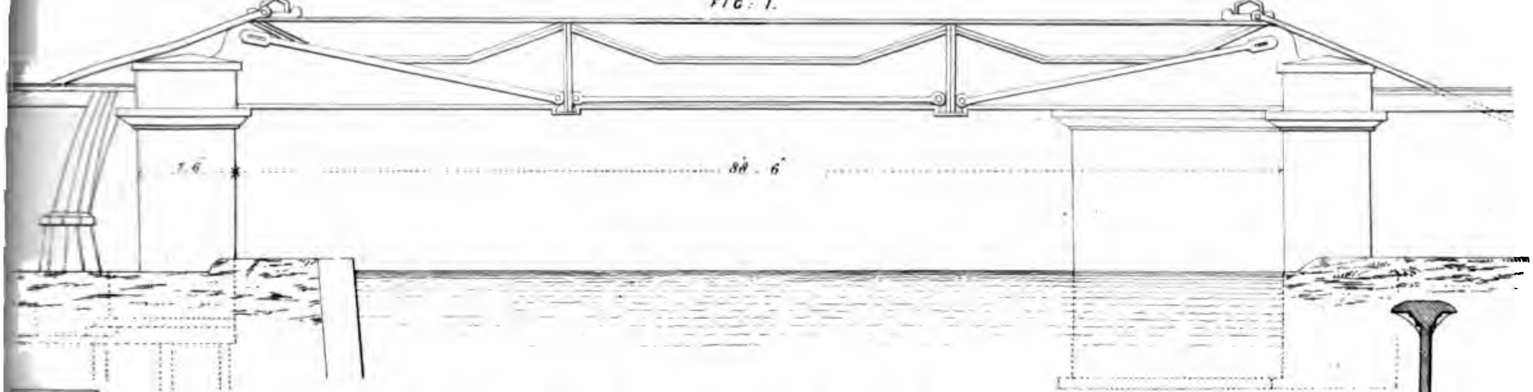


FIG: 1.

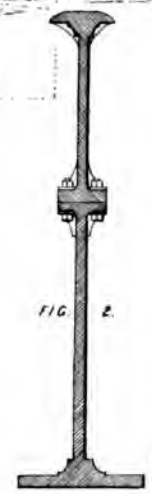


FIG. 2.

IRON BRIDGES ON THE TRENT VALLEY RAILWAY.

FIG. 4.

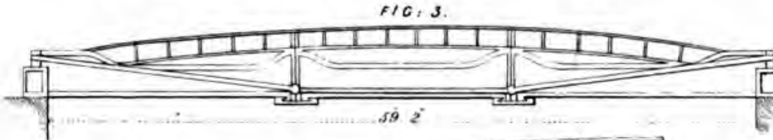


FIG: 3.

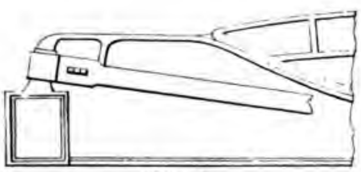


FIG: 5.

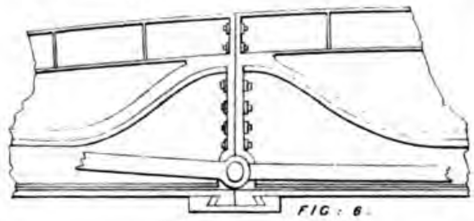


FIG: 6.

CALDER BRIDGE.

JOHN HAWKSHAW ESQ^R
ENGINEER.

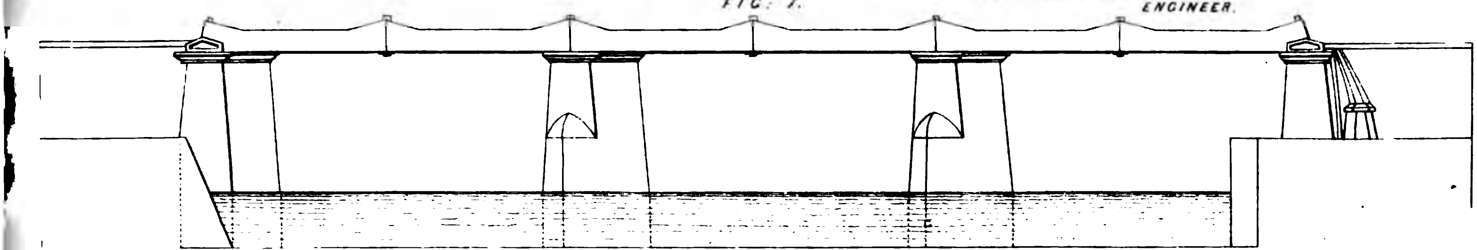


FIG: 7.

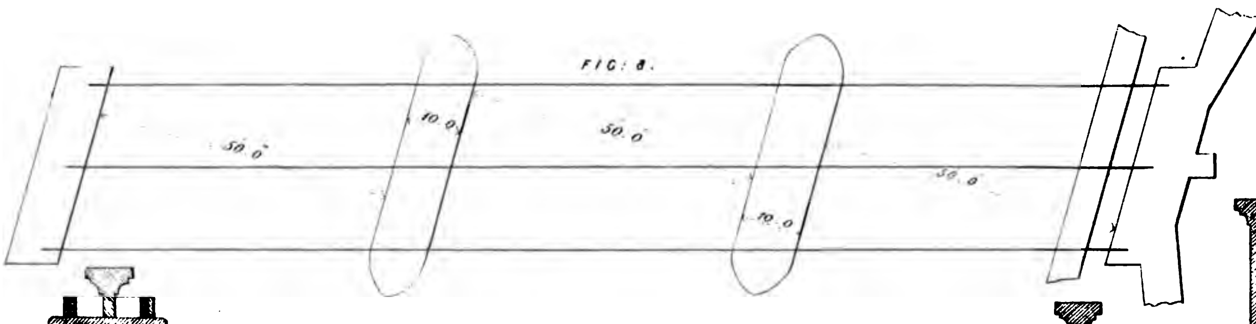


FIG: 8.

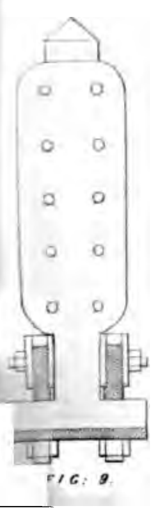


FIG: 9.

FIG: 10

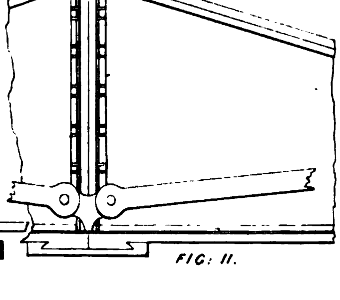


FIG: 11.

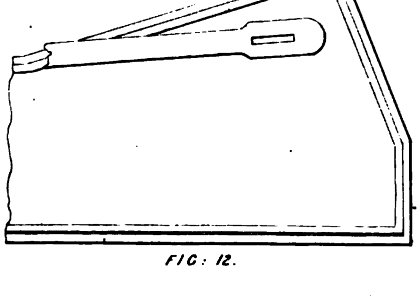


FIG: 12.

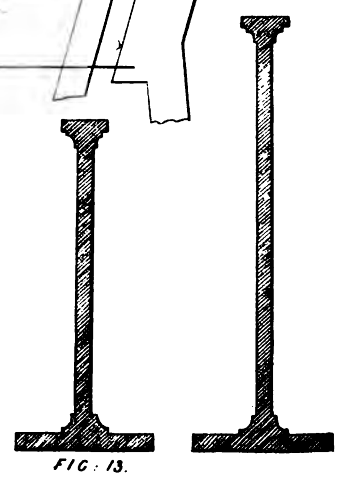
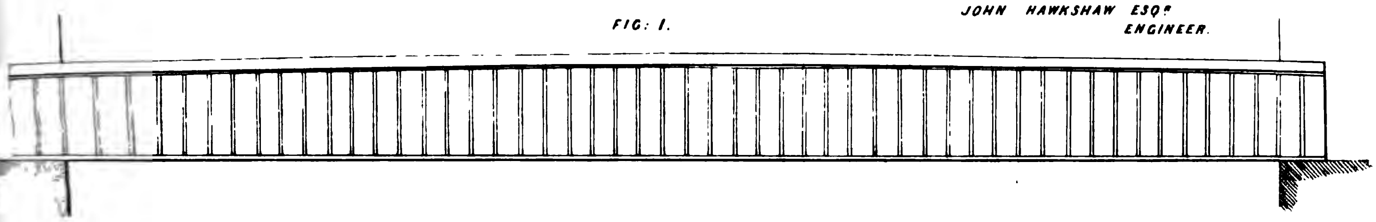


FIG: 13.

HOLLOW GIRDER BRIDGE OVER THE RIVER MEDLOCK.

JOHN HAWKSHAW ESQ^RE
ENGINEER.

FIG: 1.



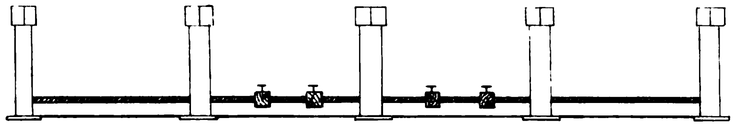


FIG: 2.

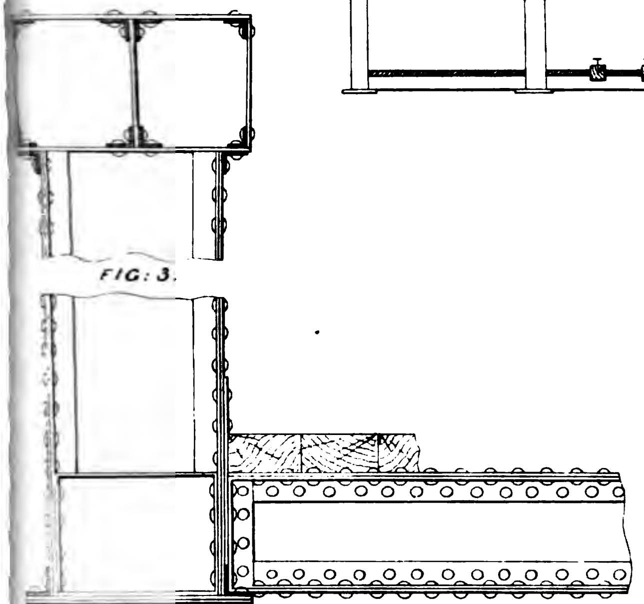


FIG: 3.

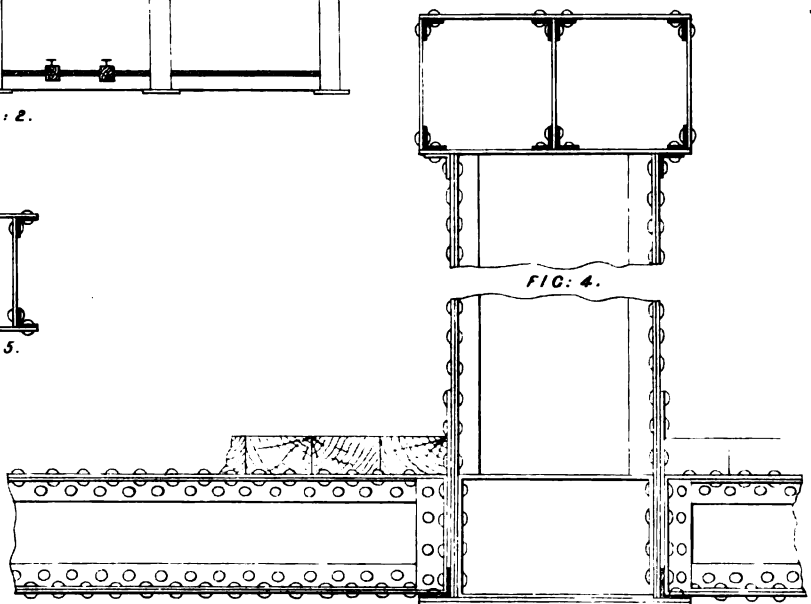


FIG: 4.

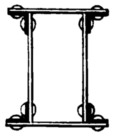


FIG: 5.

SCALE FOR FIGS: 1 AND 2.

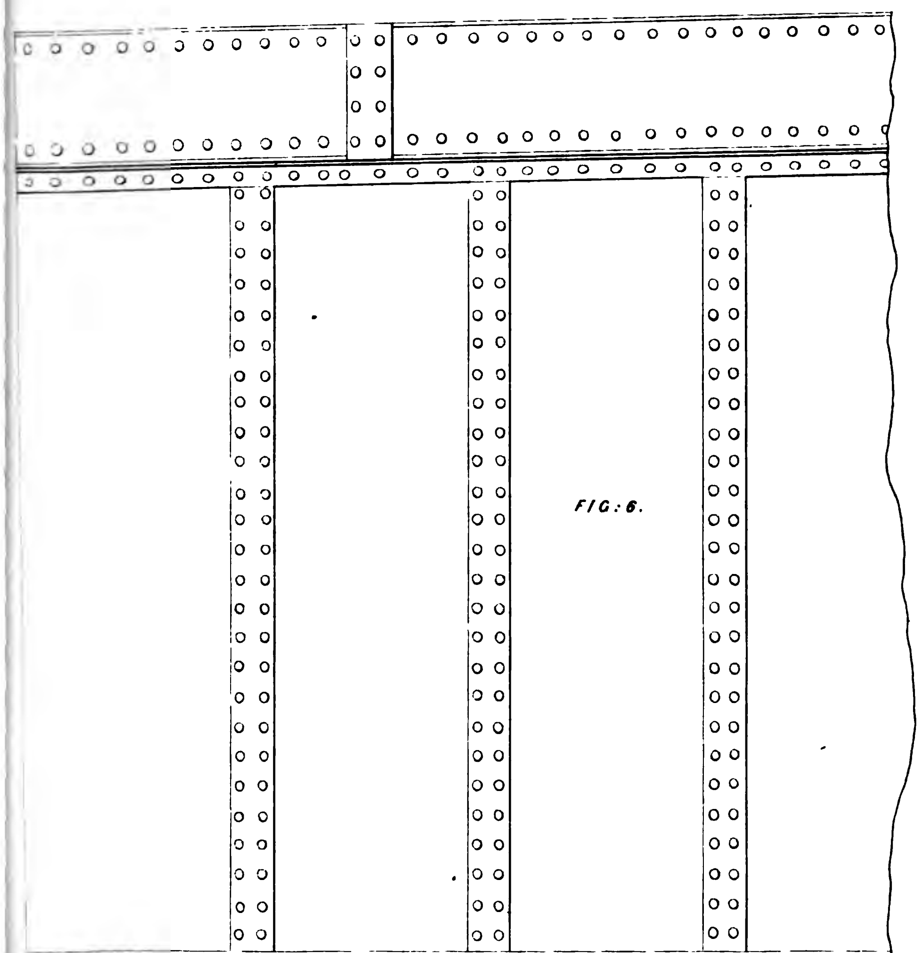


FIG: 6.

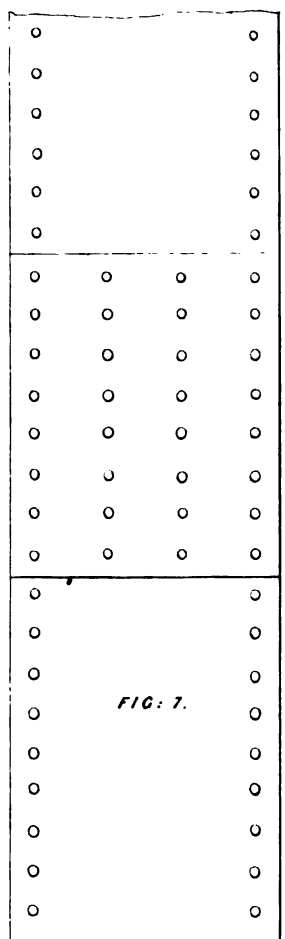


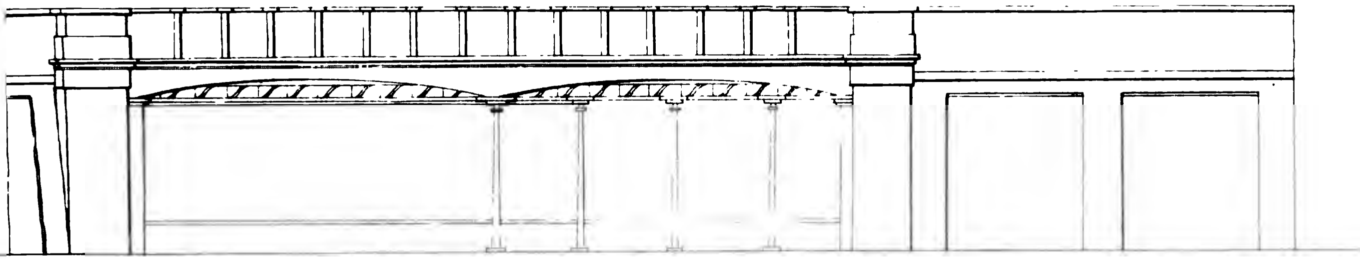
FIG: 7.

SCALE FOR FIGS: 3 TO 7.

MOUNT PLEASANT BRIDGE.

P. W. BARLOW ESQ.R
ENGINEER.

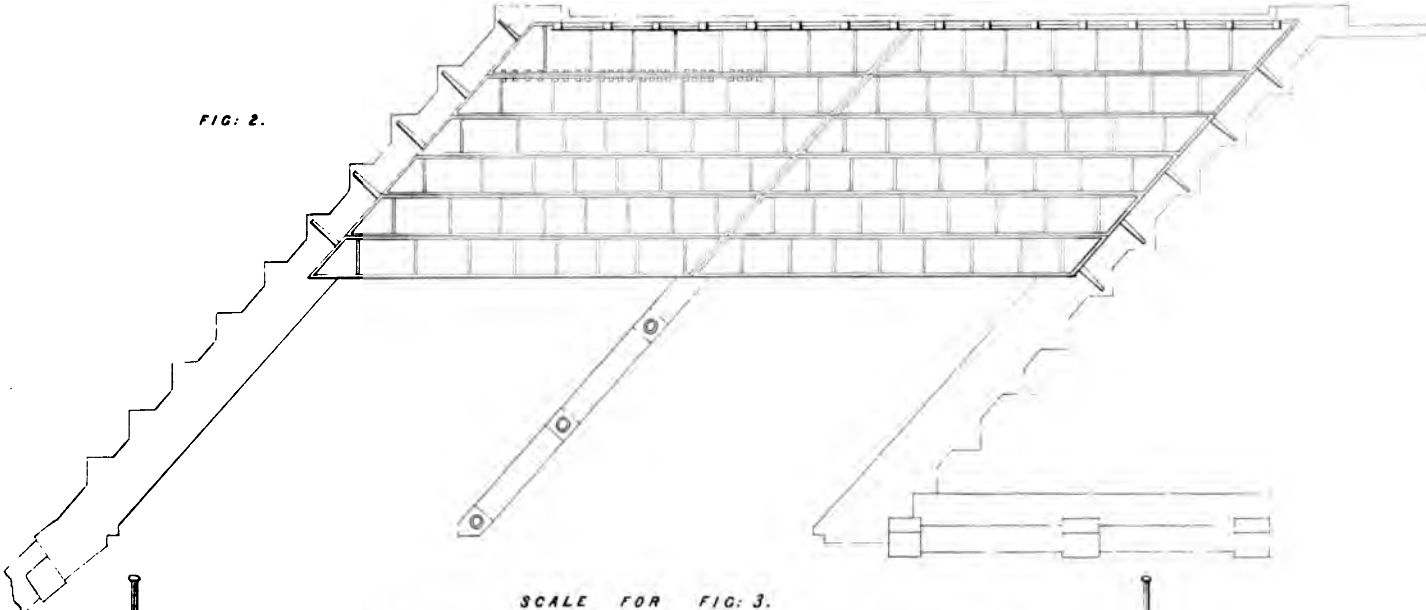
FIG: 1.



SCALE FOR FIGS: 1 & 2.

FT 10 5 0 10 20 30 40 50 FT

FIG: 2.



SCALE FOR FIG: 3.

FT 10 5 0 10 20 FT

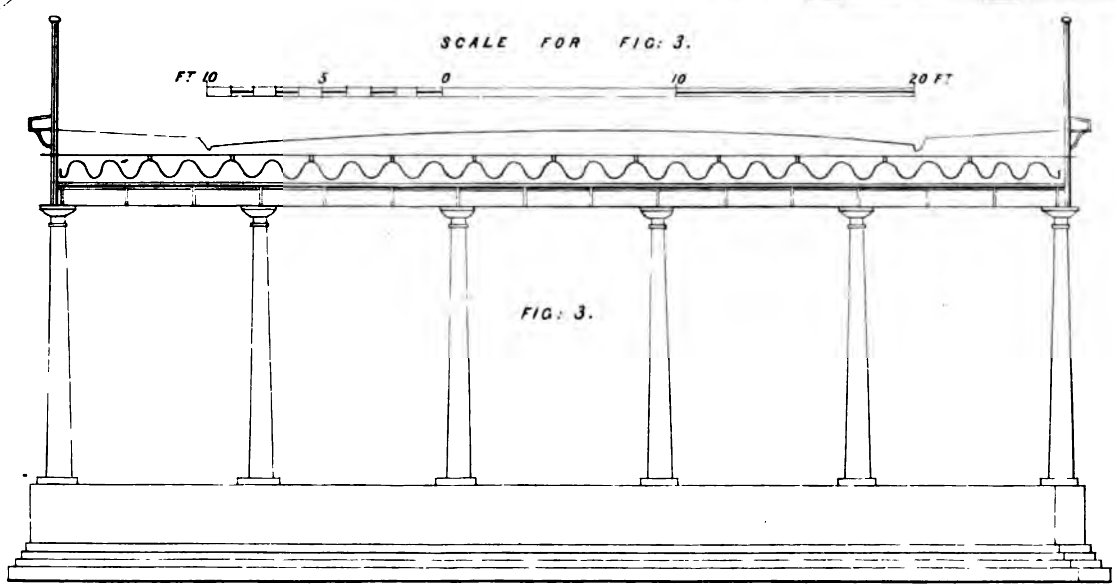


FIG: 3.

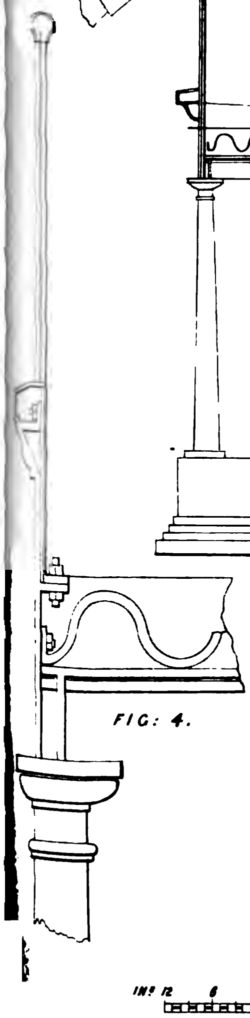


FIG: 4.

FIG: 5.

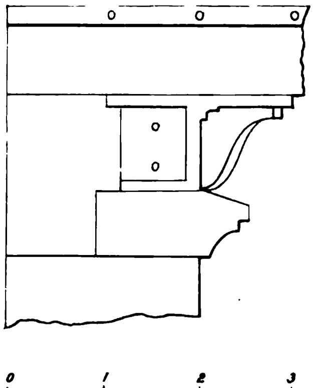


FIG: 6.

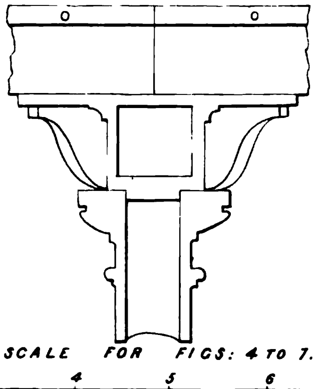
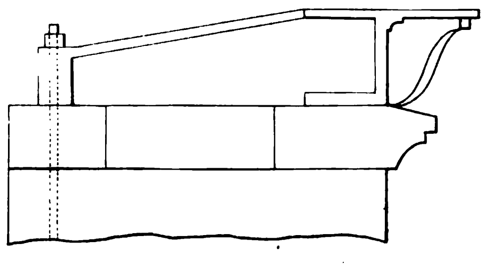


FIG: 7.



SCALE FOR FIGS: 4 TO 7.

INS 12 6 0 1 2 3 4 5 6 7 8 9 10 FT

BRIDGE FOR NEW - CROSS TURNPIKE ROAD.

P. W. BARLOW, ESQ.[r]
ENGINEER.

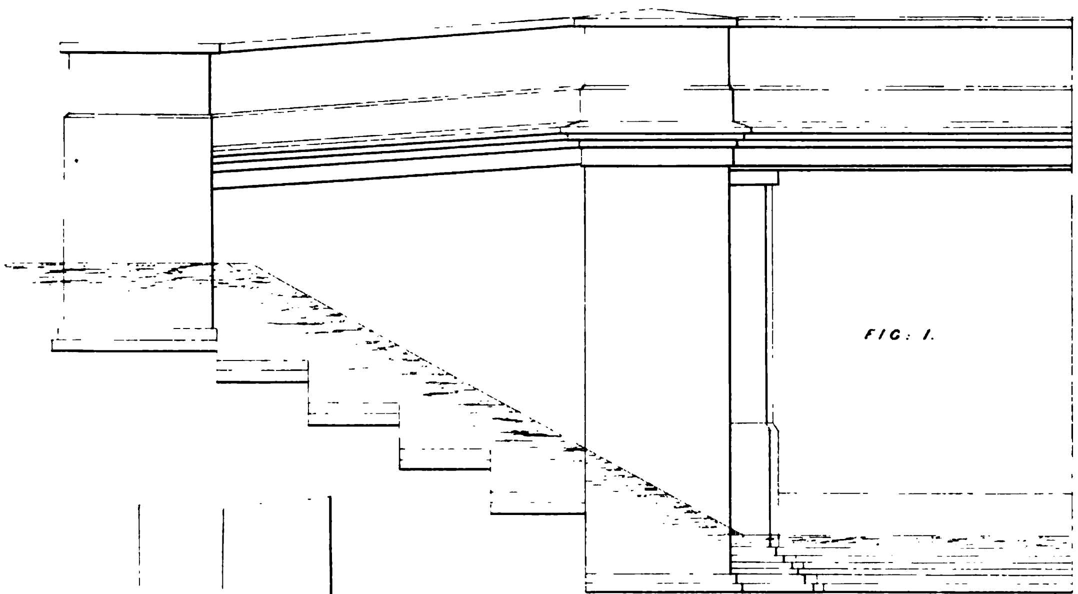


FIG: 1.

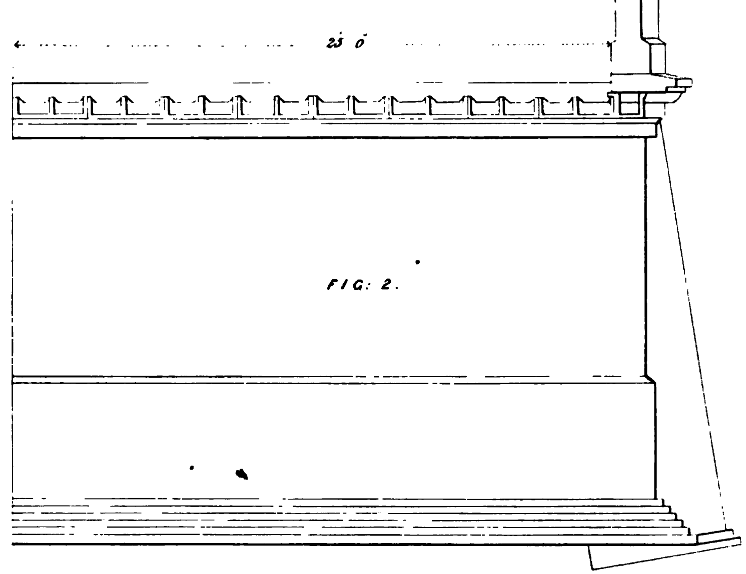


FIG: 2.

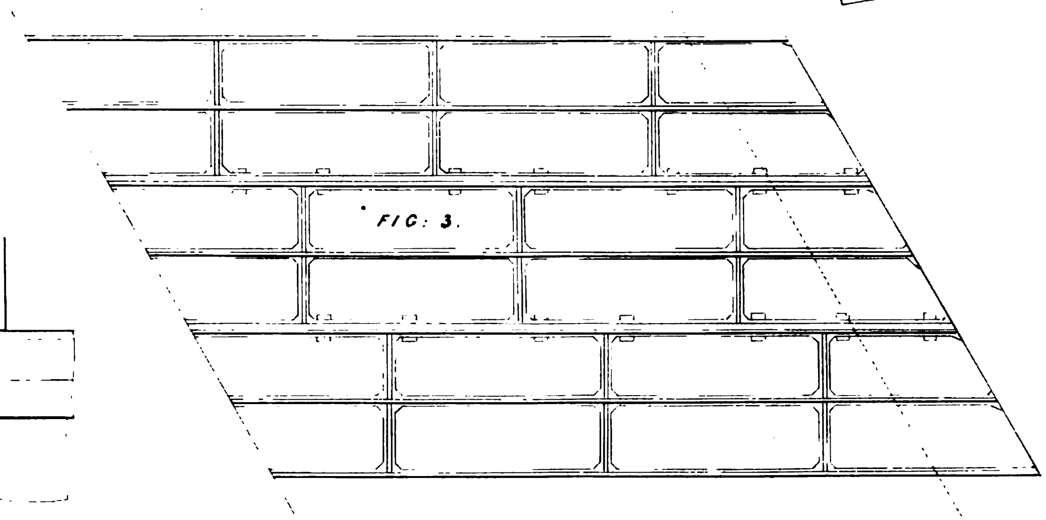


FIG: 3.

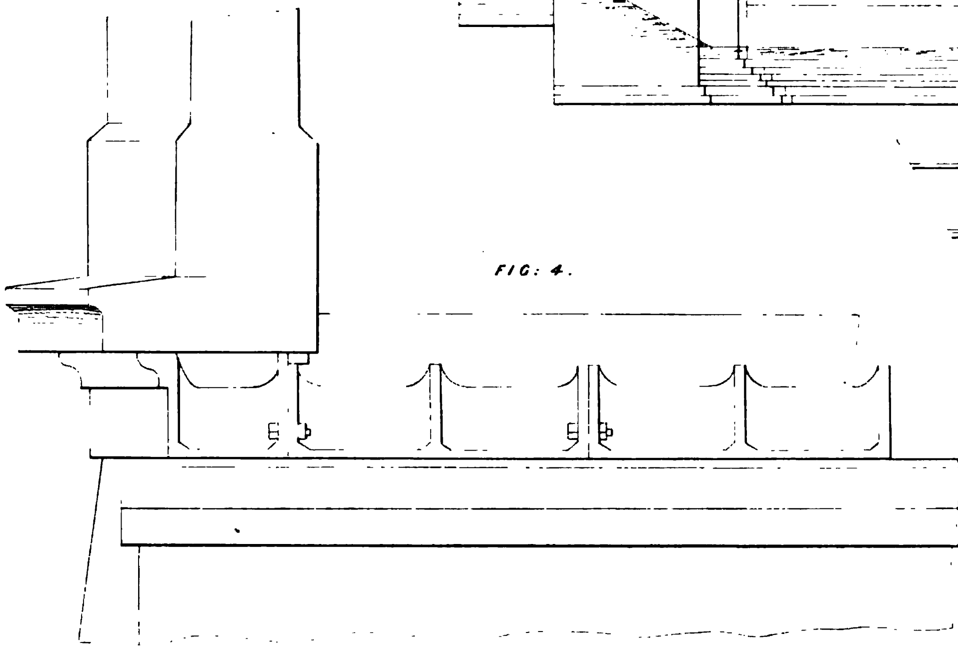
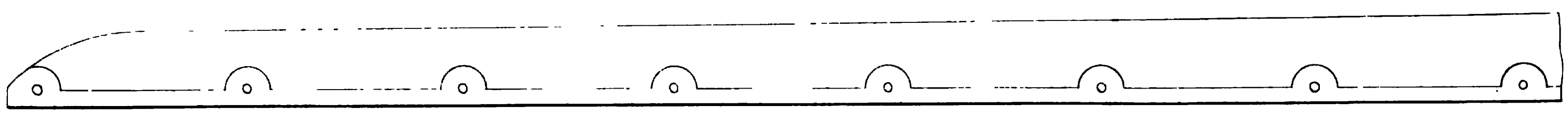


FIG: 4.

FIG: 5.


SCALE FOR FIGS: 1 & 2.

FT IN

SCALE FOR FIGS: 3. 4. & 5.

ORLESTONE BRIDGE.

P. W. BARLOW ESQ.[r]
ENGINEER.

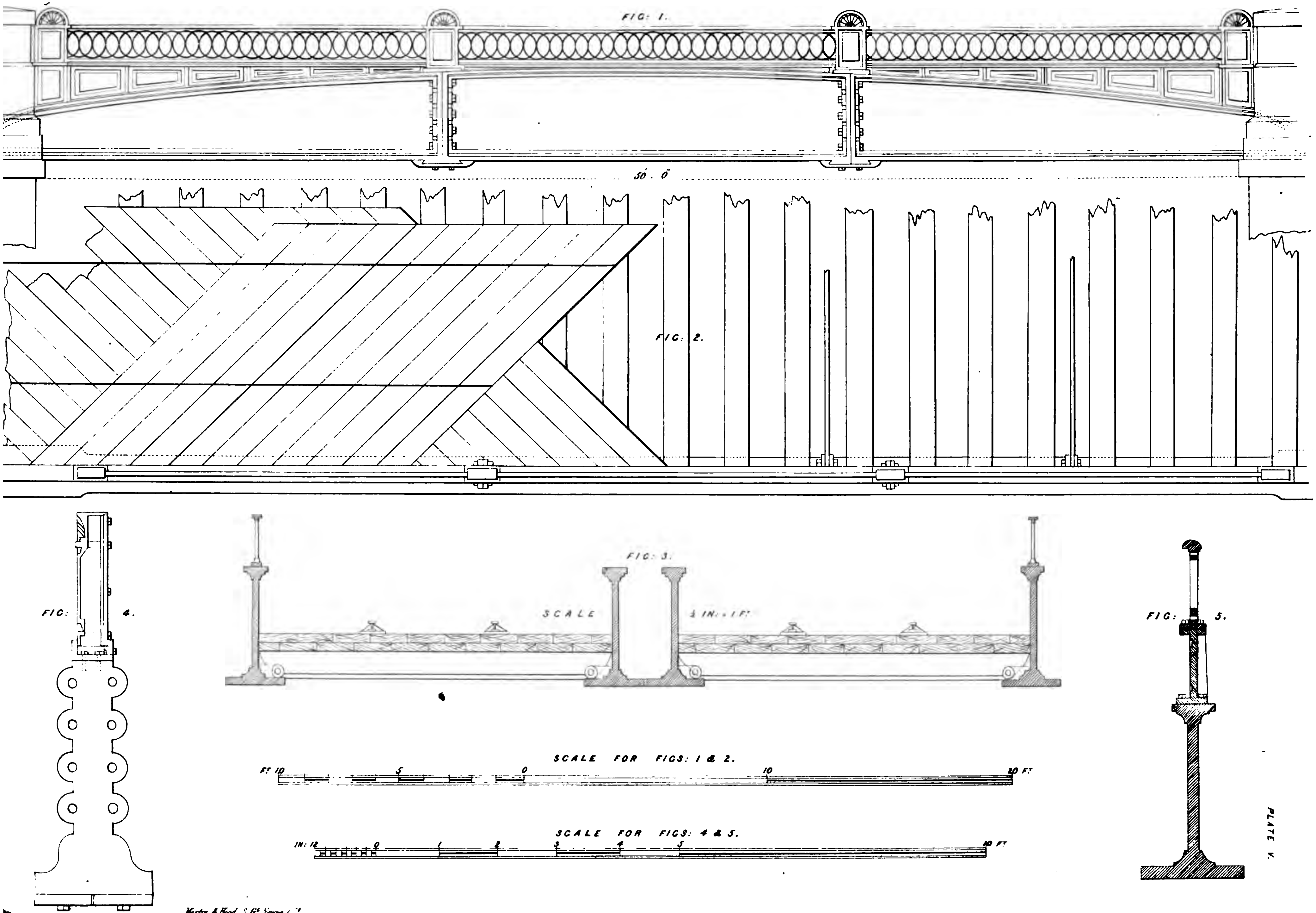


PLATE V.

PLATE VI.

CAST IRON GIRDER BRIDGES
ON THE AMBERGATE, NOTTINGHAM, AND BOSTON
AND EASTERN JUNCTION RAILWAY.

J. U. RASTRICK ESQ.R
ENGINEER.

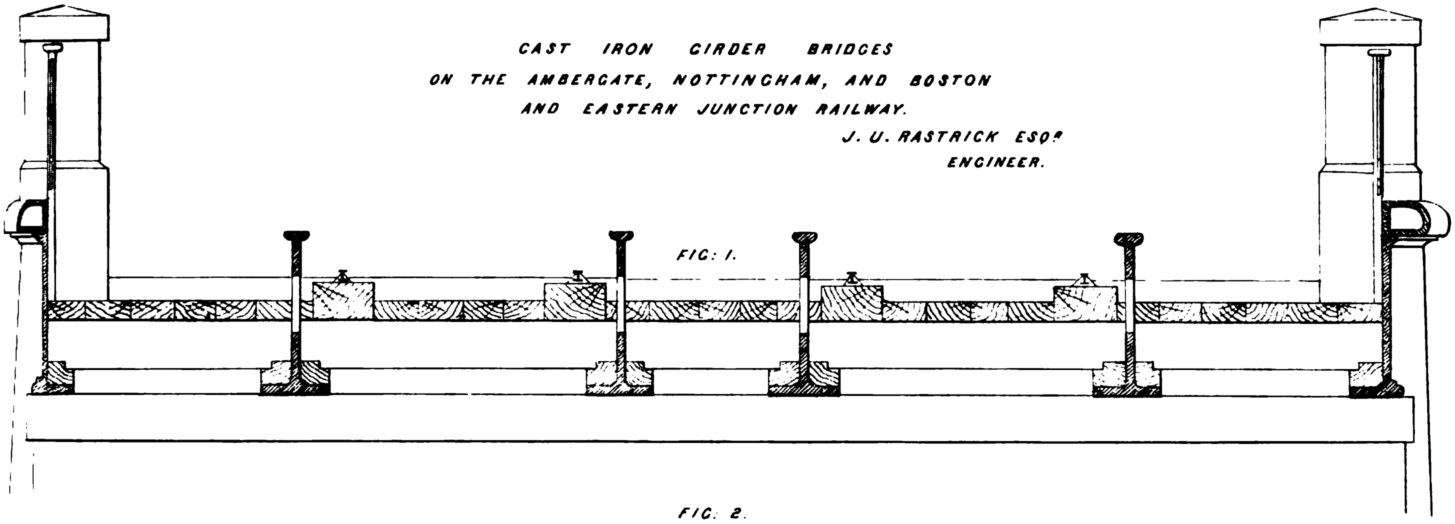


FIG: 1.

FIG: 2.

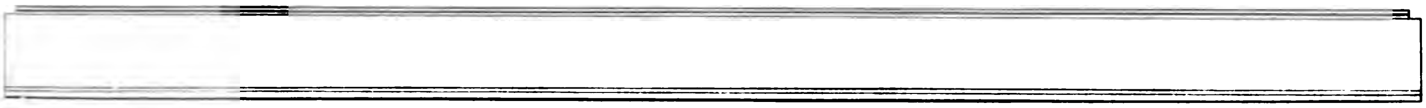


FIG: 3.

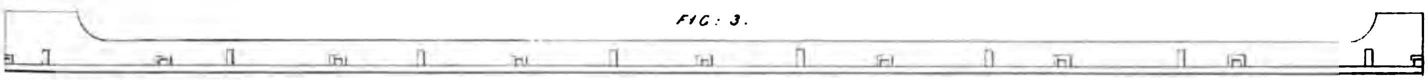


FIG: 4.

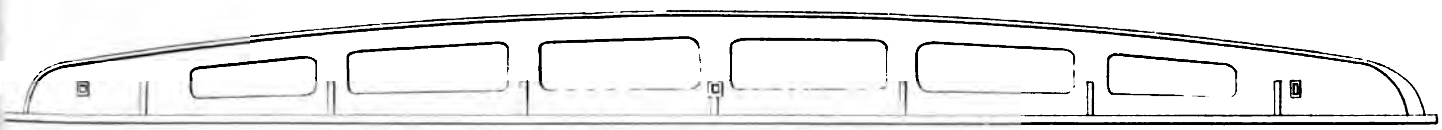
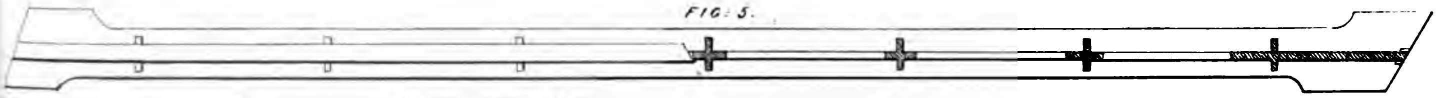


FIG: 5.



SCALE FOR FIGS: 2 TO 5.

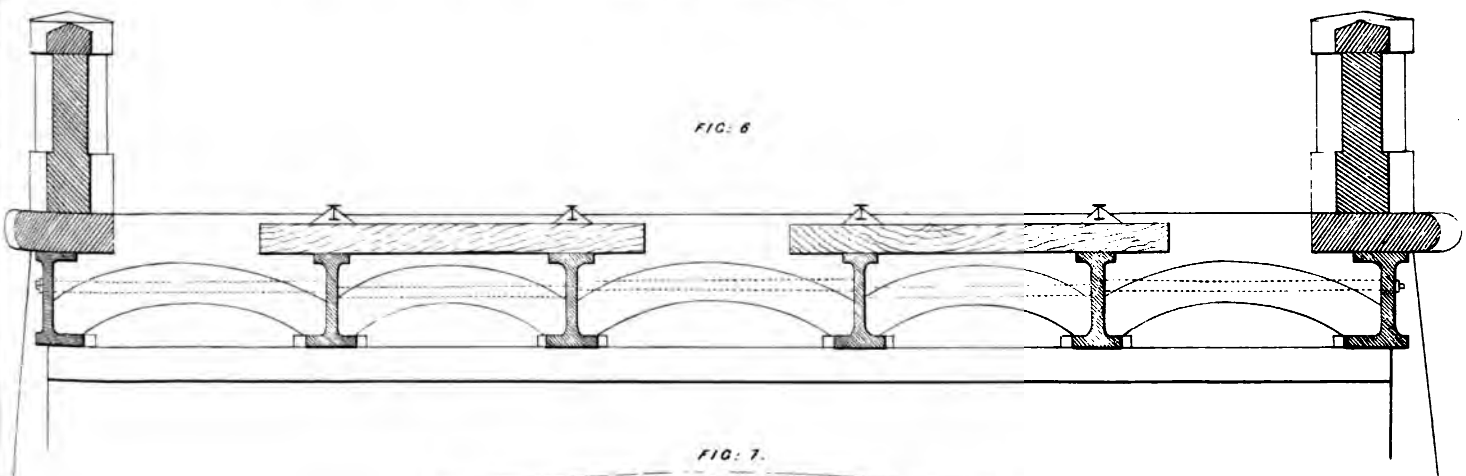
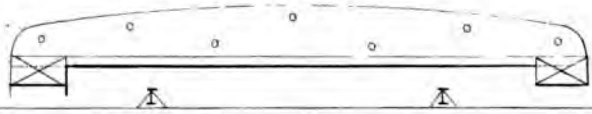


FIG: 6

FIG: 7.



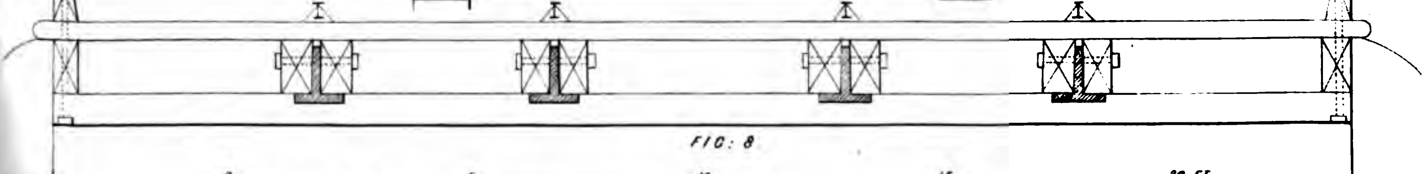


FIG: 8.

SCALE FOR FIGS: 1, 6, 7, 8.

RAILWAY BRIDGE OVER THE RIVER ARNO.

R. STEPHENSON ESQ.^R
ENGINEER.

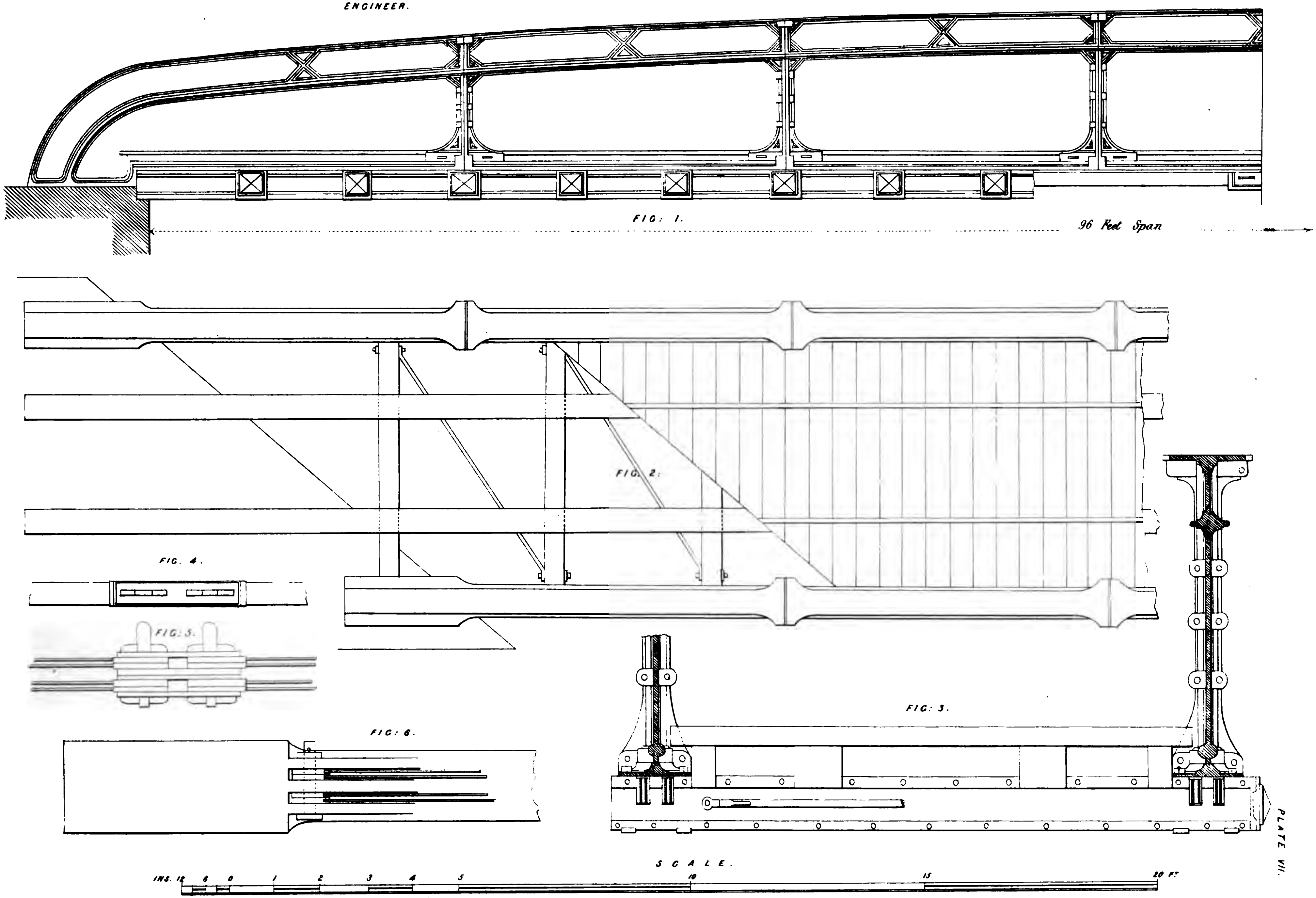


PLATE VII.

PLATE VIII.

HIGH LEVEL BRIDGE AT NEWCASTLE.

R. STEPHENSON ESQ[r]
ENGINEER.

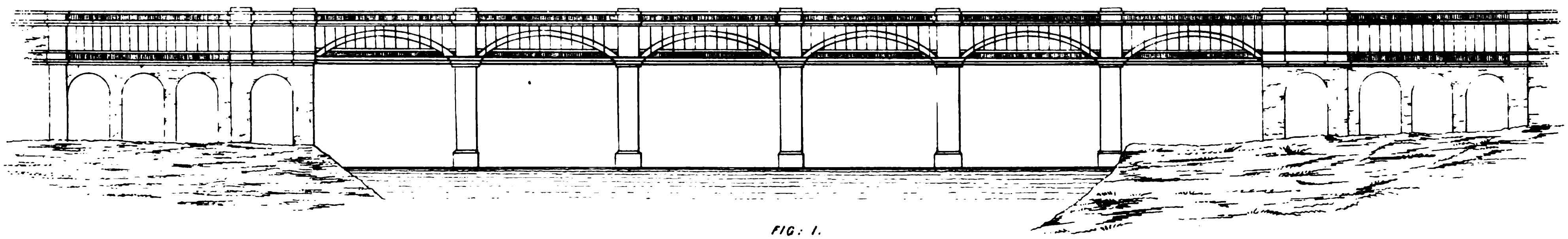


FIG: 1.

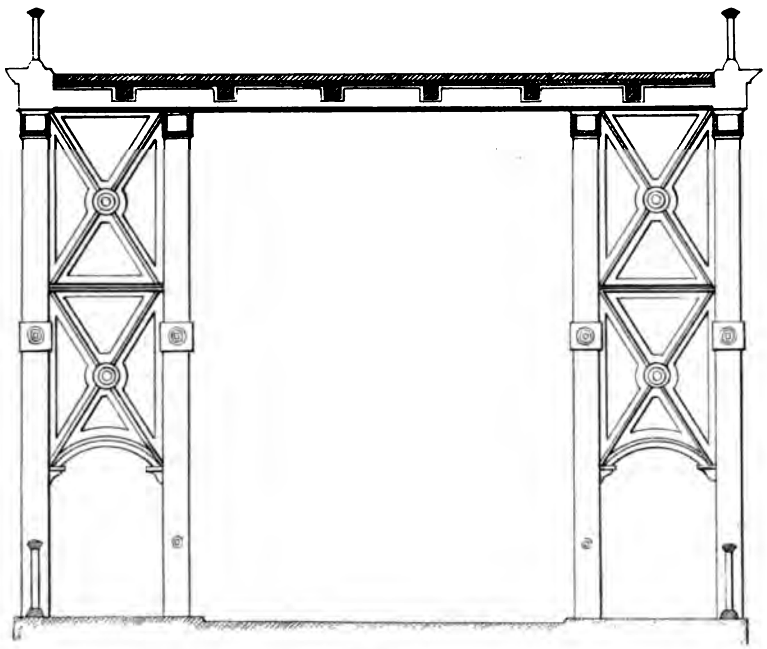


FIG. 2.

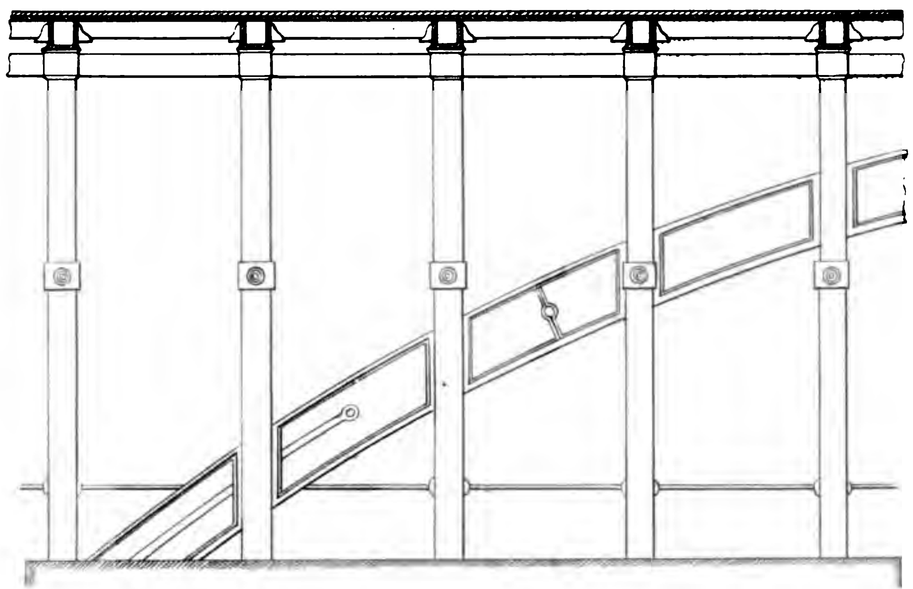
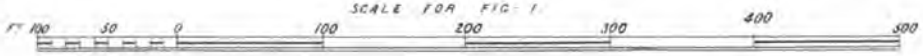
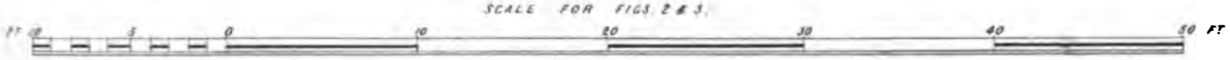


FIG. 3.

SCALE FOR FIG: 1.



SCALE FOR FIGS. 2 & 3.



CHALK FARM LANE BRIDGE.

R. STEPHENSON ESQ[R]
ENGINEER.

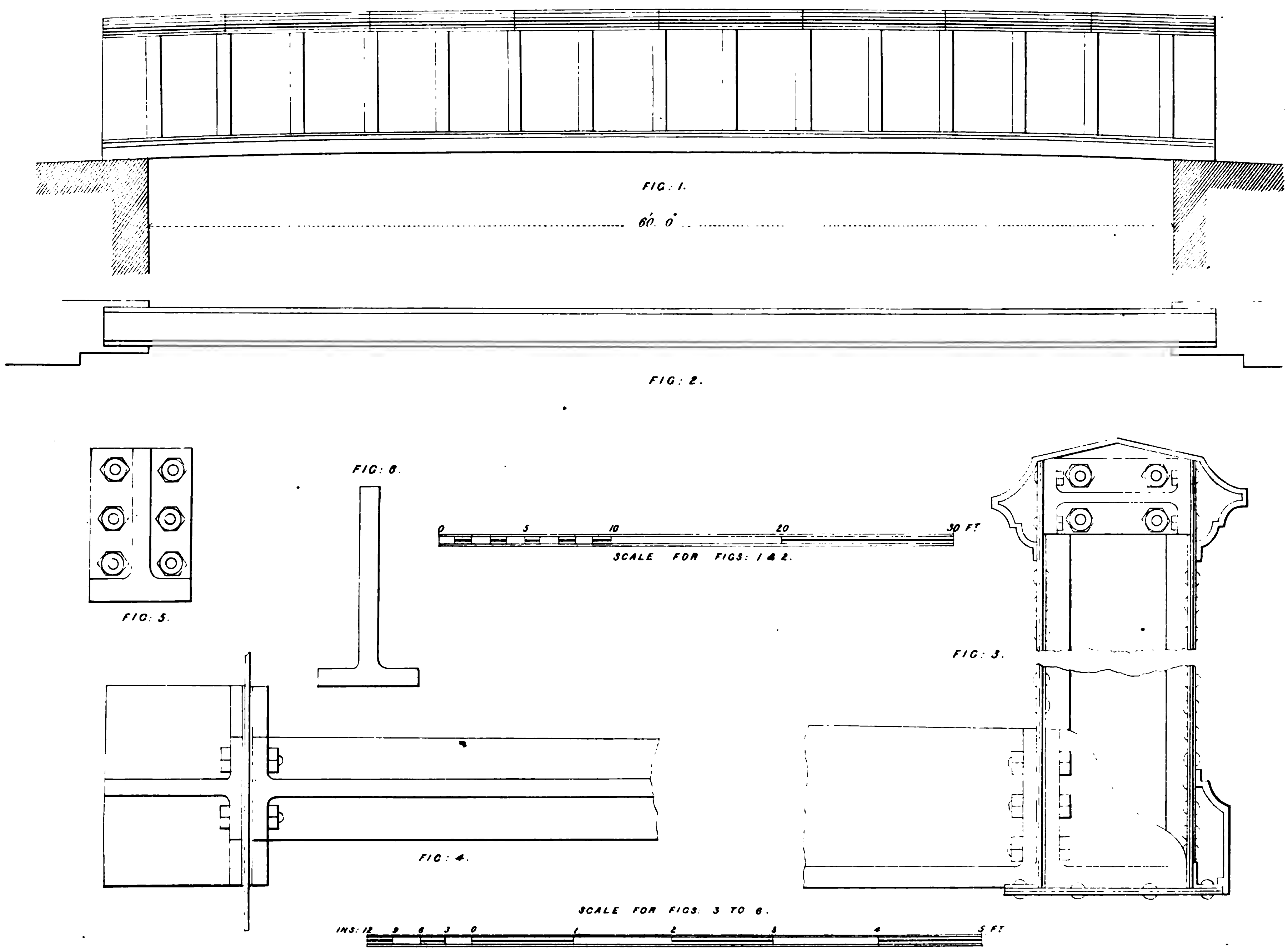
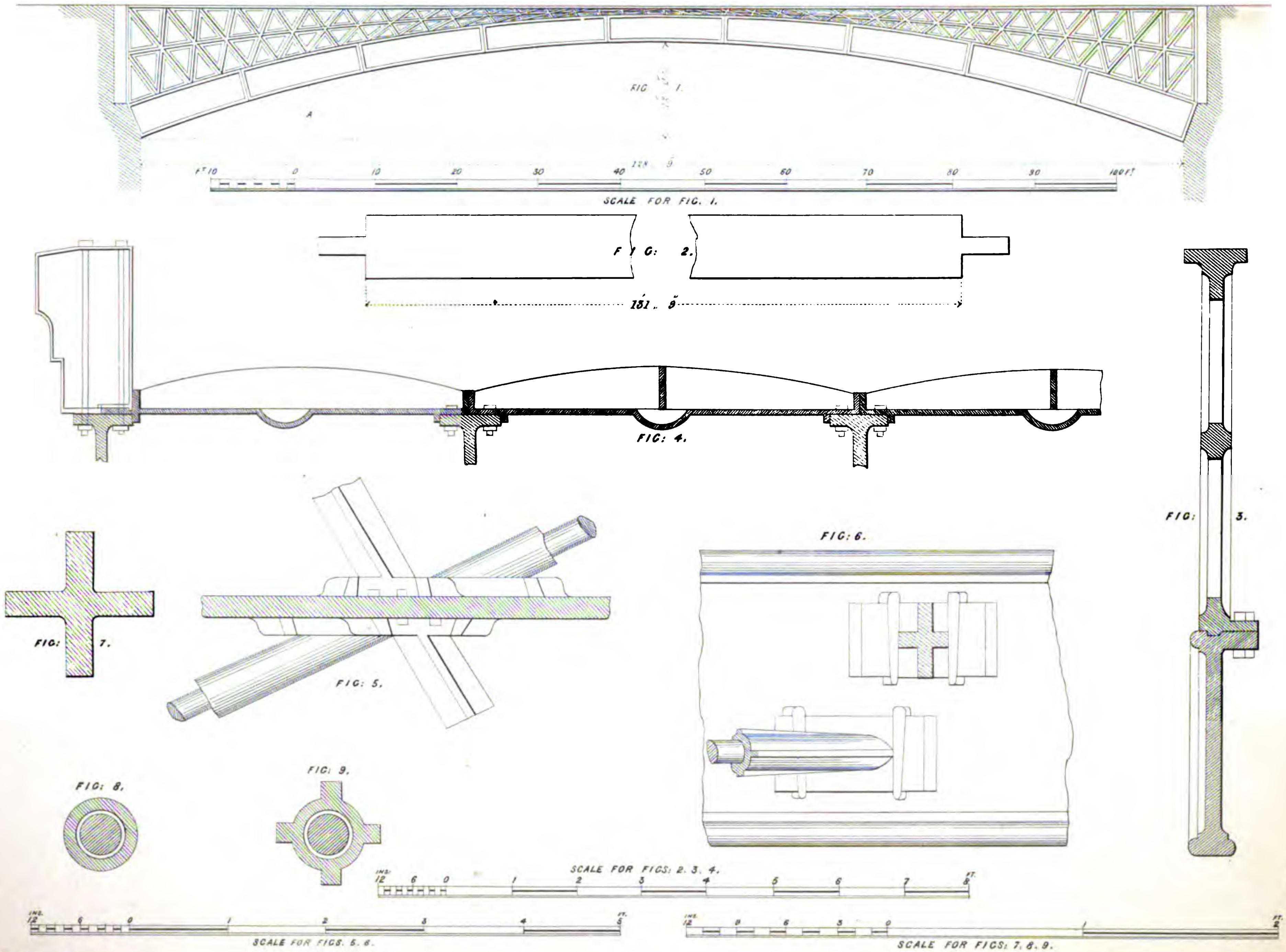


PLATE IX.

PLATE X.

CAST IRON RAILWAY BRIDGE OVER FAIRFIELD ST

C. W. BUCK ESQ^{R} ENGINEER.



...on, & Head, Gt Newport St